THE UNIVERSITY OF ALBERTA

"THE OLD FORT POINT FORMATION, JASPER, ALBERTA"

by

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A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Old Fort Point Formation, Jasper, Alberta", submitted by John Louis Weiner, M.Sc., in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

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ABSTRACT

The Late Precambrian Old Fort Point Formation in the Jasper area is 900 to 1200 feet thick and divisible into four members. Member A consists largely of blue slates. Although over most of the area green and purple slates, siltstones and limestones make up Member B, in the extreme northeast limestone-breccias make their appearance. Member C is comprised of blue slates, limestones, calcareous sandstones and a limestone-breccia, and Member D of green slates. The depth of the water in which the marine Old Fort Point beds accumulated, although shallow throughout, decreased northeastwards; the shallowest conditions were probably experienced during the formation of the limestone-breccias. Three transgression-regression cycles, corresponding to Members A and B, Member C, and Member D, have been recognized. A low-lying land, situated to the northeast and therefore probably part of the Churchill Province of the North American craton, provided the sediments.

During the Laramide orogeny rocks belonging to the Old Fort Point Formation were deformed into asymmetrical folds overturned to the northeast. The dip of the axial surfaces decreases westwards. The folds are cut by thrust and normal faults. Folds in the relatively homogeneous and incompetent Old Fort Point Formation developed by a combination of flexural-glide and shear folding along axial-plane slaty cleavage. Folds in the more competent overlying Wynd Formation developed by flexural-glide along planes parallel to bedding. Kink folds formed later than the main folds by laminar gliding on slaty cleavage planes.

Contemporaneous with the folding low-grade regional metamorphism led to (1) the

production of muscovite, chlorite and quartz by the breakdown of illite, and the albitization of feldspars. The assemblage of minerals in the rocks corresponds to the quartz-albite-muscovite-chlorite subfacies of the greenschist facies. Potassium-argon radiometric age determinations from Jasper area muscovite separates and whole-rock slate samples have yielded dates ranging from 1780 to 240 million years. These dates can be related to a westward increase in the grade of metamorphism and the grain size of the sample, smaller grain sizes having experienced more updating.

ACKNOWLEDGEMENTS

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CHAPTER I - INTRODUCTION

This thesis is concerned with the structural geology, metamorphism, stratigraphy and sedimentation of the Precambrian Old Fort Point Formation of the Jasper area, Alberta.

Geologic Setting

Ten thousand feet of Proterozoic and Lower Cambrian strata, mainly clastics, are exposed in the Main Ranges of the Canadian Rocky Mountains near Jasper, Alberta. These strata may be divided into two groups: the Gog Group, about 5000 feet of cliff-forming sandstones and quartzites, and (2) the underlying more recessive Miette Group, 5000 feet of interbedded coarse and fine-grained clastics. Because the upper part of the Gog Group contains Early Cambrian fossils, the Precambrian-Cambrian boundary has been provisionally drawn at the base of this group (Charlesworth _et al._, 1963). The Old Fort Point Formation occurs within the Miette Group, some 4000 feet below the base of the Gog Group.

The Precambrian-Lower Cambrian rocks in the vicinity of Jasper lie in the hanging wall of the Pyramid thrust fault which separates the Main Ranges from the Eastern (Front) Ranges. Rocks of the Miette Group have been tightly folded into a series of anticlinoria and synclinoria (Figure 1), whereas the overlying more competent Gog Group is characterized by larger and more open folds. Thrust, normal and wrench faults have cut the folds of both groups. The rocks of the Miette Group have undergone slight regional metamorphism.

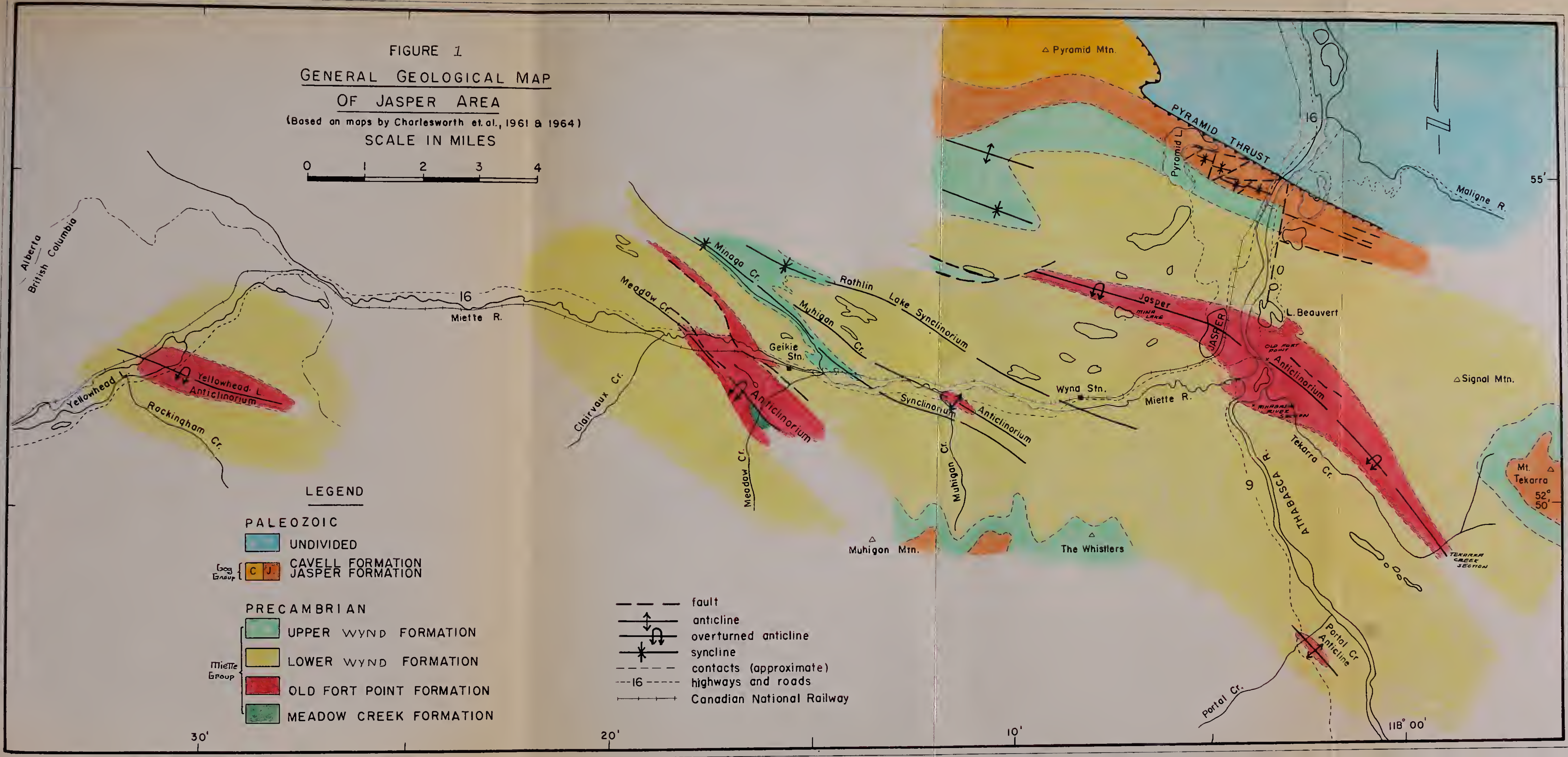


FIGURE 1
GENERAL GEOLOGICAL MAP
OF JASPER AREA
(Based on maps by Charlesworth et. al., 1961 & 1964)
SCALE IN MILES
0 1 2 3 4
Alberta
British Columbia
Yellowhead L.
Yellowhead L. Anticlinorium
Rockingham Cr.
16
Miette R.
Clairvaux Cr.
Meadow Cr.
Minaga Cr.
Anticlinorium
Geikie Stn.
Muhigan Cr.
Rothlin Lake Synclinorium
Synclinorium
Anticlinorium
Muhigan Mtn.
The Whistlers
Wyna Stn.
Pyramid Mtn.
PYRAMID THRUST
Pyramid L.
Maligne R.
Jasper
JASPER
L. Beauvert
Old Fort Point Anticlinorium
Signal Mtn.
Tekarra Cr.
ATHABASCA R.
Mt. Tekarra
Portal Cr. Anticline
Portal Cr.
LEGEND
PALEOZOIC
UNDIVIDED
Bosche Group
C J
CAVELL FORMATION
JASPER FORMATION
PRECAMBRIAN
Miette Group
UPPER WYND FORMATION
LOWER WYND FORMATION
OLD FORT POINT FORMATION
MEADOW CREEK FORMATION
fault
anticline
overturned anticline
syncline
contacts (approximate)
highways and roads
Canadian National Railway
30'
20'
10'
118° 00'
55'
52° 50'

History of Research

The history of research on the Precambrian rocks of the Main Ranges in the Jasper area can be divided into two phases. During the first phase, which extended from 1898 to the late 1950's, research was of an exploratory nature and did not involve any appreciable geological mapping or measurement of stratigraphic sections. Since 1959, detailed mapping and study of the Precambrian along the Athabasca and Miette River valleys has been in progress. Mapping at the scale of 1-inch-to-2-miles has been completed in an area of the Main Ranges to the northwest of Jasper townsite.

Early Research

Around the end of the nineteenth century, McEvoy 1901 traversed the route from Edmonton, Alberta to Tête Jaune Cache, British Columbia. He recognized the existence of a great fault, now known as the Pyramid thrust fault, which separated the Devonian and Carboniferous of the Eastern Ranges from the older rocks of the Main Ranges.

The stratigraphy from Jasper to Tête Jaune was divided by McEvoy into two parts. The Bow River "series", to which a Cambrian age was assigned, consisted in descending order of: (1) conglomerate, pebbly in places and gritty in others, (2) fine-grained conglomerates with interbedded grey and greenish-grey slates, and (3) a thick sequence of argillites, dark grey to black in color, associated with thin calcareous sandstones. These rocks, which apparently coincide with parts of the Gog and Miette Groups, were called the Bow River series because of their similarities to the Bow River conglomerates named by Dawson (1886). Overlying the Bow River series, the Castle Mountain "group" of supposed Upper Cambrian age consisted of about 1500 feet of dolomite capped by

1400 more feet of grey quartzite. This section is exposed on Yellowhead Mountain and at the present time would be included in the Miette and Gog Groups.

McEvoy continued as far west as the Rocky Mountain Trench and reported that the rocks on the southwest side were a great series of mica schists. He correlated them with the Shuswap "series" of southern British Columbia and regarded them as Archaean in age.

Walcott (1913, p. 340) was the first to use the term "Miette" (Table 1). He described the rocks cropping out along the Miette River valley as

> "Belt Series, Miette Formation–massive-bedded gray sandstones with thick bands of gray and greenish siliceous shales....2000'".

Although the Miette-Cambrian contact was not observed, Walcott stated that an erosional unconformity exists between them.

In 1929, a Harvard University Expedition travelled throughout the Jasper-Mount Robson area (Collet and Paréjas, 1932) but added little to our knowledge of the details of the Precambrian stratigraphy. Raymond (1930), a member of the Harvard Expedition, gave the name Cavell Formation to the quartzites exposed on Mount Edith Cavell. They are now included in the Gog Group.

The name Jasper "series" was proposed by Allan *et al.* (1932, p. 231) for a series of rocks which, where

> "...exposed in the neighborhood of the town of Jasper consists of grey to buff-colored quartzites, argillites, sedimentary breccias, slates and many conglomerate beds. The thickness of the series is unkown, but it probably amounts to several thousand feet....it is overlain by quartzites believed to be Lower Cambrian in age".

TABLE 1: Stratigraphic Nomenclature of the Precambrian and Lower Cambrian Rocks of the Jasper Area

	Walcott 1913	Raymond 1930	Allan et al. 1932	Charlesworth et al. 1961 and 1962	Mountjoy 1962	This Thesis
Lower Cambrian and Older (?)		Cavell Formation	Cavell Formation	Cavell Formation	Gog Group	Cavell Formation
			Jasper "series" / Miette Formation	Jasper Formation		Jasper Formation
Precambrian Proterozoic	Miette Formation	Miette Formation		Miette Formation	Miette Group	Wynd Formation
				Old Fort Point Formation		Old Fort Point Formation
				Unnamed Sandstone		Meadow Creek Formation

They distinguished these rocks from rocks cropping out along the Miette River valley which Walcott (1913) had called Miette. The Jasper series is now included within the Gog Group.

Sorensen (1955) gave some general information about the Precambrian geology on the northeast side of the Rocky Mountain Trench near Mount Robson but did not include any stratigraphic sections.

Recent Research

In 1959, Dr. H.A.K. Charlesworth of the Department of Geology of the University of Alberta in Edmonton initiated a program of mapping the Precambrian and Lower Cambrian strata in the vicinity of Jasper and westward along the Yellowhead Pass route (Charlesworth and Remington, 1960; and Charlesworth *et al.*, 1961). Since that time, seven graduate students at the University of Alberta have carried out detailed investigations of selected areas within the larger area (Remington, 1960; Evans, 1961; Stauffer, 1961; Griffiths, 1962; Steiner, 1962; Akehurst, 1964; and Bielenstein, 1964).

These workers have provisionally divided the Precambrian-Lower Cambrian succession into five formations (Table 1). The oldest rocks are a previously unnamed series of sandstones, conglomerates and slates that underlie the Old Fort Point Formation in the Meadow Creek Anticlinorium. It will be referred to in this thesis as the Meadow Creek Formation. The Old Fort Point Formation consists of about 1200 feet of slates, siltstones, bedded limestones and limestone breccias. The Miette Formation can be divided into two parts: a lower member 2500 feet thick and composed of pebble-conglomerates, sandstones, siltstones and slates; and an upper 1600-foot-thick member,

predominantly slates. Overlying the Miette Formation with apparent conformity is the Jasper Formation, 1500 feet of feldspathic and conglomeratic sandstones. The Cavell Formation, which overlies the Jasper, was not investigated in detail but appears to consists largely of quartzite. The Meadow Creek, Old Fort Point and Miette Formations have been assigned to the Proterozoic while the Jasper and Cavell Formations are assigned to the Lower Cambrian.

Mountjoy (1961 and 1962) of the Geological Survey of Canada, has mapped the SE 1/4 of the Mount Robson sheet at the scale of 1-inch-to-2-miles. About one third of this map-area consists of the Main Ranges to the northwest of Jasper townsite. Mountjoy (1962, p.3) has chosen to use Walcott's term "Miette" as a group name. He has redefined the Miette Group "....to include all the strata beneath Lower Cambrian Gog quartz sandstones in the Mount Robson district and the northern and western parts of Jasper National Park". The Jasper and Cavell Formations mentioned above would be included in the Gog Group whereas the Meadow Creek, Old Fort Point and Miette Formations would belong to the Miette Group.

Stratigraphic Nomenclature Used in This Thesis

The stratigraphic nomenclature used in this thesis is given in Table 1. The name "Meadow Creek Formation" is proposed by this author for the strata underlying the Old Fort Point Formation. The Meadow Creek Formation will be defined in Chapter 2. Recognizing that it is contrary to the Code of Stratigraphic Nomenclature (1961, p. 654) to use the term "Miette" for both a group and a formation within the group, this writer has decided to replace the name "Miette Formation" with the name "Wynd Formation".

The name "Wynd" is derived from Wynd Station, a siding on the Canadian National Railways about 2 miles west of Jasper townsite where there are excellent exposures of the formation. The previous descriptions of the Wynd (Miette) Formation given by Charlesworth and Remington (1960) and Charlesworth et al. (1961 and 1963) are considered adequate and, therefore, the formation is not redefined in this thesis.

Scope of the Project

This author has mapped the structure of the Old Fort Point Formation and adjacent strata in the Portal Creek, Muhigan Creek, Meadow Creek and Yellowhead Lake Anticlinoria (Figure 1). The mapping was carried out to establish the structural geometry of the deformed rocks. This information has been augmented by the author's study of microscopic and submicroscopic fabrics in order to reconstruct the sequence of tectonic events, the movements that took place during periods of deformation, and the orientations of the principal stresses that caused the rocks to deform.

The variations in low-grade metamorphism with structural, stratigraphic and geographic position, as well as with lithology, have also been studied. The stratigraphic relationships and petrography of the Old Fort Point and Meadow Creek Formations were investigated in order to determine the conditions of deposition of these strata.

The conclusions reached in the various areas of this investigation are given at the ends of the respective chapters and sections.

CHAPTER 2 - STRATIGRAPHY AND SEDIMENTATION

Introduction

The general stratigraphy and stratigraphic nomenclature of the Jasper area is discussed in Chapter 1. This chapter is concerned mainly with the Meadow Creek and Old Fort Point Formations, the oldest known rocks of the area. The Meadow Creek Formation, was measured along Meadow Creek, the only place it is definitely known to crop out. The Old Fort Point was first examined in detail by Evans (1961) who confined his study to the Jasper Anticlinorium. This writer, in addition to studying the formation in the Jasper Anticlinorium, has measured sections in all other known areas of outcrop, namely the Portal Creek, Muhigan Creek, Meadow Creek and Yellowhead Lake Anticlinoria (Figure 1).

Folding and low-grade metamorphism have created obstacles in the study of these formations. Outcrops are limited to the cores of a small number of isolated anticlinoria in which the rocks are strongly deformed. In spite of this, composite sections have been built up. Thickness measurements are suspect because limbs of folds have been thinned relative to the axial regions. Metamorphism has in many instances destroyed sedimentary features and many minerals have recrystallized. Rocks that were originally shales are now well-cleaved slates and even phyllites.

Thin sections were cut from selected lithologic samples and examined under the petrographic microscope. Some uncovered thin sections were stained to determine the abundance and nature of feldspars present. X-ray diffraction techniques were used to determine the minerals present and to detect variations in their relative abundances.

Sedimentary structures were studied in cut and polished rock slabs and the heavy minerals of a number of samples were separated, identified and counted.

Meadow Creek Formation

Introduction

The term "Meadow Creek Formation" is used by this writer to designate the predominantly arenaceous strata that underlie the argillaceous Old Fort Point Formation in the Meadow Creek Anticlinorium. These rocks, previously referred to as, "an unnamed series of sandstones, conglomerates and argillites" (Charlesworth *et al.*, 1961, p. 5) and "Formation A" (Charlesworth *et al.*, 1963, p. 3), have not been described previously.

The Meadow Creek Formation crops out only along the banks of Meadow Creek about one and one-quarter miles from its mouth (Figure 1). The contact with the conformably overlying Old Fort Point slates is placed at the top of the highest pebbly sandstone. Only 130 feet of section are exposed.

Description

The ratio of arenaceous to argillaceous strata in the section is about 6 to 1 (Figure 2). Conglomerate beds make up about one half of the arenaceous beds and medium- to coarse-grained and pebbly sandstones the remaining half.

The conglomerates which make up about 45 percent of the section are usually grey in color and weather a rusty brown. Beds of conglomerate range in thickness from 6 inches to 15 feet although most are about 1.5 feet thick. Successive beds of conglomerate occur in units 5 to 20 feet thick.

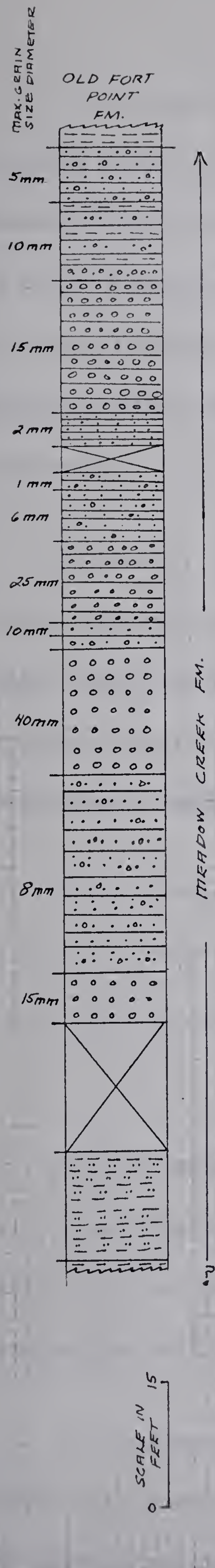
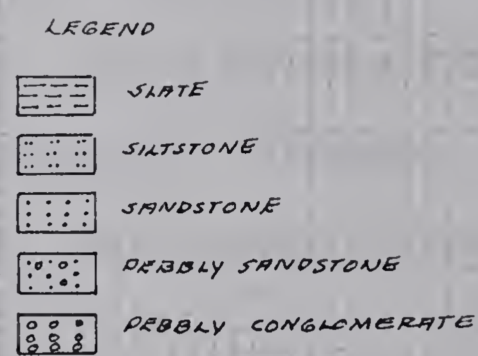


FIGURE 2

SECTION OF MEADOW CREEK FORMATION EXPOSED ALONG MEADOW CREEK



The Meadow Creek conglomerates are pebble conglomerates. The maximum size of pebbles varies from unit to unit (Figure 2). The largest pebbles are about 40 mm in diameter. They are subrounded to well rounded, whereas the sand grains in the matrix are usually subangular. The conglomerates themselves are poorly sorted. Depending on the sample, 65 to 95 percent of the pebbles are quartz pebbles. Most of the remaining pebbles are albite, although some metamorphic rock fragments do occur in the coarser conglomerates.

The matrix, which makes up about 20 percent of the conglomerates, consists largely of sand-sized quartz and subsidiary albite. Staining techniques indicate that potash feldspar is not present in the Meadow Creek section. In addition to the sand-sized fraction, the matrix consists of fine-grained calcite, siderite, micas, albite and quartz. The matrix seldom exceeds 10 percent.

The conglomerates may be classified as orthoconglomerates because the pebbles are usually in contact with each other and because they are quantitatively far more important than the matrix.

About 40 percent of the section is made up of medium - to coarse-grained sandstone with or without pebbles. Beds range in thickness from 3 inches to 6 feet and average about 1 foot. The thickest sandstone unit is 22 feet thick. Color is very uniform; grey on a fresh surface and rusty brown on a weathered surface.

The sandstones are poorly sorted (Plate VII-8) and the sand grains subangular. Eighty-five to ninety-five percent of the sand grains are quartz, the remainder albite. Rock fragments are rare. Matrix does not usually amount to more than 15 percent of

the rock and consists of fine-grained calcite, siderite and micas.

If one uses Travis' (1955) sandstone classification, the Meadow Creek sandstones fall in the feldspathic and quartz sandstone fields.

The siltstones and slates are poorly exposed and were not examined in detail. The siltstones occur in beds 1 to 2 inches thick and weather rusty brown. The slates are bluish-grey in color, poorly laminated, and weather to an olive grey color.

Old Fort Point Formation

Introduction

The name Old Fort Point Formation was first used by Charlesworth and Remington (1960, p. 12) to designate the recessive sequence of metamorphosed slates, limestones and siltstones that underlie the more resistant, predominantly arenaceous Wynd Formation. Old Fort Point is a historical landmark southeast of Jasper townsite where excellent exposures of the formation occur. Evans (1961) studied the Old Fort Point Formation in the Jasper Anticlinorium and measured an incomplete section about 1200 feet thick. The base of the formation is not exposed there but the upper contact was drawn at the base of the lowest quartz pebble conglomerate of the Wynd Formation. Evans subdivided the Old Fort Point into four members. This writer has found Evans' subdivisions to be useful in mapping the formation in other parts of the Jasper area and has retained his basic system of nomenclature. In some cases it has been possible to subdivide his members into smaller units. The members are briefly described below in ascending order (see Figure 3) and their thickness variations are summarized in Table 2.

Figure 3 Composite Sections of The Old Fort Point Formation in the Old Fort Point (East) and Meadow Creek (West) Areas.

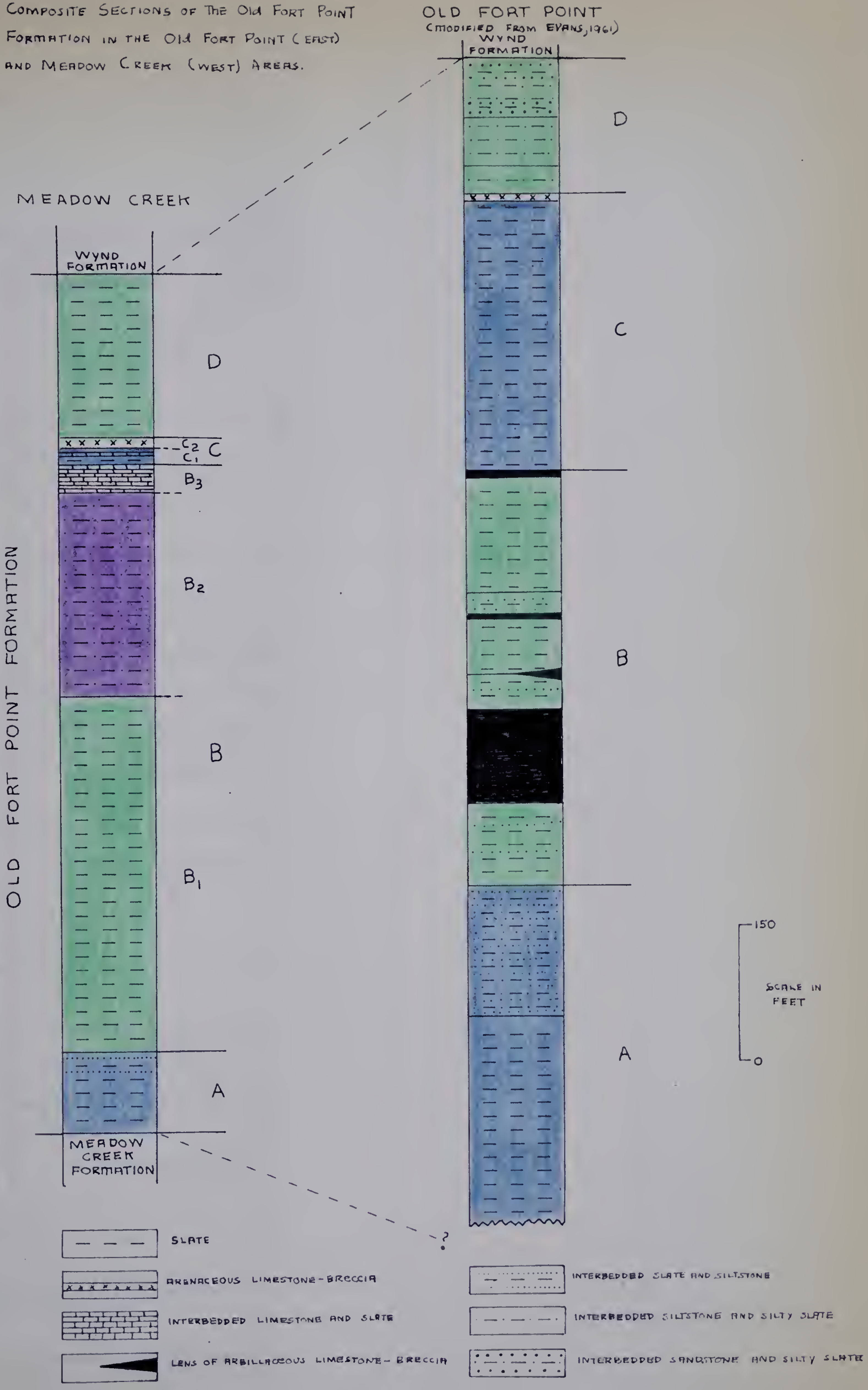


Table 2 Thickness in Feet of Members of Old Fort Point Formation. The precise location of each section is given in Appendix A.

			LOCATION OF STRATIGRAPHIC SECTIONS						
			Old Fort Point	Mina Lake	Tekarra Creek	Portal Creek	Muhigan Creek	Meadow Creek	Yellowhead Lake
WYND FORMATION									
OLD FORT POINT FORMATION	D	Green Slates and Siltstones	150		60*	60*	160	275	
	C_2	Arenaceous Limestone-Breccia	1-10		9-14	20	25	2-10	
	C_1	Bluish-Grey Slates Calcareous Sandstones and Blue Limestones	90-250		22	10	——	1-10	
	B_3	Bedded Limestones or Argillaceous Limestone-Breccia		40*	40	26*	50*	35	
	B_2	Purple Siltstones and Slates	480		75			230	100*
	B_1	Green Slates and Siltstones			90*			390	250-350
	A	Bluish-Grey Slates	350*					90	350-425*
MEADOW CREEK FORMATION								175*	

* INDICATES PARTIAL SECTION

Member A 90 to 425 feet of dark bluish-grey slates with interbedded rustyweathering siltstones. In the Meadow Creek Anticlinorium, the base of Member A is drawn at the top of the highest pebbly sandstone of the Meadow Creek Formation.

Member B This member can be divided into a widespread southwestern and a restricted northeastern facies. The southwestern facies consists in ascending order of about 650 feet of green to grey slates (B_1), purple slates and siltstones (B_2), and interbedded limestones and slates (B_3). The northeastern facies, restricted to parts of the Jasper Anticlinorium consists of about 480 feet of alternating slates, siltstones and intraformational limestone-breccias.

Member C 3 to 250 feet of dark bluish-grey slates which weather a rusty brown. An arenaceous limestone-breccia, 1 to 20 feet thick, is present at the top of the member throughout much of the area. The breccia is usually underlain by a few feet of interbedded limestones, sandstones and dark bluish-grey slates.

Member D 150 to 275 feet of green and grey slates with silty laminae. In the Portal Creek section, a 5-foot thick quartz-pebble limestone-breccia occurs about 60 feet above the base of the member. Member D is conformably overlain by the Wynd Formation.

Member A

Evans' (1961) type section of Member A is located on the northeast bank of the Athabasca River about 900 feet southeast of the bridge that crosses the river at Old Fort Point. He measured (ibid., p. 2) "350 feet of dark bluish grey argillite [slate] with interbedded siltstones near the top". The base of the member is not exposed in the Jasper Anticlinorium, but it can be seen in the Meadow Creek area where the base is drawn at the top of the highest pebbly sandstone of the Meadow Creek Formation. The contact there is conformable. A total section of only 90 feet was measured in the Meadow Creek area (Figure 3). The top of the member was drawn at the top of an interbedded slate and siltstone sequence. The B_1 slates above the contact are dark grey to green in color, are conformable with those below, and contain relatively few siltstone beds.

Member A. 90 to 125 feet of dark [illegible] thin-bedded [illegible]. In the [illegible] Creek [illegible], the base of Member A is drawn at the top of the highest pebbly sandstone of the [illegible] Creek formation.

Member B. This member can be divided into a [illegible] sandstone unit [illegible] factors. The [illegible] feet of green to gray [illegible] and [illegible] bedded limestones and [illegible]. The [illegible] of the [illegible] about 480 feet of [illegible] and [illegible].

Member C. [illegible] feet of dark [illegible] limestone-[illegible]. [illegible] throughout much of the area. [illegible] feet of [illegible] limestone, [illegible], and dark [illegible].

Member D. 180 to 170 feet of green and gray [illegible]. In the [illegible] Creek section, a [illegible] feet above the base of the member. Member D [illegible] formation.

Member A

[illegible] (1951) [illegible] of Member A [illegible] River [illegible] of the [illegible]. The [illegible] 500 feet [illegible] bedded [illegible] near the top. The base of the [illegible] limestone, but [illegible] Creek [illegible] the top of the highest pebbly sandstone of the [illegible] Creek formation. [illegible] A [illegible] section of only 90 feet [illegible] (Figure 2). The top of the member was drawn [illegible] sequence. The E_1 [illegible] gray to green [illegible] with those below, and [illegible].

The only other known section of Member A is in the Yellowhead Lake Anticlinorium. Outcrops are poor and thicknesses must be estimated from structural cross sections. Member A is probably 350 to 425 feet thick here. The top and bottom are not exposed but the appearance of a thick sandstone bed near the base is suggestive of the Meadow Creek Formation.

The dark bluish-grey slates of Member A weather a dark grey color with occasional rusty iron oxide films. In hand specimen, they appear to be poorly laminated; however, in thin sections from the Meadow Creek area, they can be seen to be very thinly laminated. They consist largely of muscovite and chlorite flakes 0.03 mm and less in diameter. Books of chlorite up to 0.08 mm in diameter and occasionally interleaved with muscovite make up about 3 percent of the total. Member A slates contain only a very small percentage of quartz, albite and calcite compared to other Old Fort Point slates. This is evident in thin sections and X-ray diffraction patterns. Samples of Member A slates from Yellowhead Lake have extremely well-developed slaty cleavage and resemble phyllites. Rusty weathering siderite rhombs about 0.1 mm in diameter are scattered throughout all the slates and siltstones.

The bedded siltstones near the top of Member A in the Meadow Creek area are greenish-grey in color, weather brown, and are in beds 0.5 to 2 inches thick. Individual beds are 6 to 18 inches apart. The consist of about 25 percent finely crystalline calcite*

*Throughout this thesis, Folk's classification (1962) will be used in referring to the size of calcite grains: very coarsely crystalline (1-4 mm), coarsely crystalline (0.25-1.0 mm), medium crystalline (0.062-0.25 mm), finely crystalline (0.016-0.062 mm), very finely crystalline (0.004-0.016 mm), and aphanocrystalline (0.004 mm and less).

and 60 percent angular grains of quartz and albite 0.05 mm and less in diameter. The remainder is composed of fine-grained muscovite and chlorite, and some siderite, and occasional flakes of brown biotite up to 0.15 mm in diameter. The biotite flakes have an altered appearance and similar ones were observed by this writer in Evans' thin sections of Member A siltstones from the Jasper Anticlinorium. In some thin sections the siltstones display cross-lamination.

The amount of siltstone at the top of Member A is greater in the Jasper Anticlinorium than in the Meadow Creek Anticlinorium.

Member B

Over most of the Jasper area, Member B. consists of (B_1) green to greenish-grey slates with some siltstones, (B_2) purple silty slates and siltstones, and (B_3) interbedded limestones and calcareous slates (Figure 3). This sequence will be referred to as the "southwestern facies" of Member B. On the northeast limb of the Jasper Anticlinorium, Member B consists of greenish-grey slates interbedded with siltstones and argillaceous limestone-breccias. These more restricted lithologies will be referred to as the "northeastern facies" of Member B.

Southwestern Facies - Member B_1

The "type section" proposed for this member is along Meadow Creek where a presumably complete section of 390 feet of slates was measured. A similar thickness has been calculated for the Yellowhead Lake Anticlinorium. The member consists of a monotonous sequence of greenish to greenish-grey slates, characterized by a general lack of siltstone beds. The upper contact of B_1 is very distinctive, consisting of an abrupt color change to the conformable purple slates and siltstones of B_2. The color

change at the base of B_1 is more gradational.

(i) Slates - Member B_1 slates in the Meadow Creek area weather a light grey or greenish-grey color. They are usually extremely well cleaved and smooth to the touch; some can be classed as phyllites. The occasional thin silty laminae are less than 1 mm thick and weather dark brown or black. In thin section the slates are seen to consist primarily of small (0.012 mm or less in diameter) flakes of chlorite and muscovite. X-ray patterns suggest that the proportion of muscovite to chlorite is lower in the green slates of B_1 than in the bluish-grey slates of Member A (see Chapter 4). The percentage of silt-sized particles of quartz and albite is very small, about 5 to 10 percent. Books of chlorite comprise 1 to 2 percent of the rock. Finely crystalline calcite scattered randomly throughout the slates or in very thin laminae comprises 5 to 10 percent and is therefore more common than in Member A. Siderite is also more abundant, comprising about 1 to 2 percent of the rock here and even more in the slates from Yellowhead Lake.

(ii) Siltstones - The few siltstone beds present contain 30 percent or more of medium to coarsely crystalline calcite. The remainder is comprised of angular grains of quartz and albite and abundant books and flakes of chlorite.

Southwestern Facies - Member B_2

The distinguishing characteristic of this member are its purple color, high silt content, and high percentage of calcite. It is easily recognized in the field. The member thickens westward from 75 feet in the Tekarra Creek section to 235 in the Meadow Creek area. The lower 10 feet or so of the member are laminated slates. Above this the member becomes more silty. The upper contact of the member with the limestones of B_3 is grad-

ational, consisting of a 5- to 15-foot-thick zone in which purple and pinkish limestones first appear and then increase in number until they are dominant over the interbedded calcareous purple slates.

(i) Slates - The greyish-purple silty slates of Member B_2 are visibly laminated; thin calcite-rich laminae show up as light pink against a darker background. Bedding surfaces often have a scattering of muscovite flakes less than 0.5 mm in diameter. Chlorite-muscovite books make up as much as 10 percent of the rocks along with 5 to 10 percent of silt-sized grains of quartz and albite. As much as 20 percent is untwinned finely to coarsely crystalline calcite which is either randomly distributed or concentrated in thin laminae. The bulk of the rock is muscovite and chlorite flakes. Occasionally small grains of siderite are present.

All the purple beds of Member B_2 contain 1 to 2 percent detrital grains of magnetite. Many of the magnetite grains have reddish films of hematite on them. This probably accounts for the purple color of the rocks. Small portions of Member B_2 that are light green were found to be lacking in magnetite. Miller and Folk (1955) have made similar observations.

The calcareous B_2 slates from Yellowhead Lake are finer grained (Plate X-6) than those farther east. The silt-sized quartz and albite are better sorted, make up 5 to 10 percent of the rock, and are 0.016 to 0.048 mm in diameter. Siderite is more abundant and occurs as rhombs up to 1 mm in size.

(ii) Siltstones - The purple calcareous siltstones may contain as much as 40 percent of untwinned, medium crystalline calcite. The remainder of the rocks consist of angular silt grains of quartz and albite around which are wrapped flakes of muscovite and chlorite.

Siderite makes up 1 to 2 percent.

Southwestern Facies - Member B_3

The distinctive interbedded limestones and slates of Member B_3 range in thickness from 30 to 60 feet. The member has been observed in the Athabasca River and Tekarra, Portal, Muhigan and Meadow Creek sections. At Yellowhead Lake the part of the section where it would be expected is not exposed.

The member can be roughly divided into two parts, a lower one consisting of pinkish or purplish limestones and interbedded purple calcareous slates, and an upper one of light grey limestone and interbedded green calcareous slates.

In the Meadow Creek area, limestone accounts for about 65 percent of the member, slate about 35 percent (Plate I-4). Limestone beds range in thickness from less than 1 inch to about 6 inches with the average being about 3 inches. Slate beds average 50 percent thinner. Bedding in the limestone is quite uniform and individual beds can be traced laterally for distances of more than 100 feet. In the upper few feet of the member, where silty slate predominates over limestone, the limestone beds are less continuous.

A number of sedimentary structures can be seen in the strata of Member B_3. Zones of intraformational limestone-breccia, up to 8 feet long and 1 foot thick, are found scattered throughout the section, being more common near the top. The phenoclasts are unworn fragments of disrupted limestone beds and the matrix is calcareous slate or argillaceous siltstone. Some of the breccias are "edgewise" with the piled up phenoclasts usually inclined toward the east. Small-scale cross-bedding is visible on the weathered surfaces of many silty limestones. What appears to be asymmetrical ripple marks (Plate

II-6) are common in the limestones. The steep sides of the structures always face the west. Desiccation cracks in limestone beds are present in the upper part of the member in the Athabasca River and Tekarra Creek sections. Zones of incipient brecciation are also present (Plate II-4).

(i) Limestones in Thin Section - The limestones consist of 85 percent or more finely crystalline to aphanocrystalline calcite. The average grain size is remarkably uniform in most samples and is of the order of 3 to 4 microns. According to Folk (1962), they would be classified as micrites, rocks consisting of microcrystalline calcite ooze. The calcite grains are usually angular (Plate IX-5) and show no evidence of having been transported. The remainder of the limestones is made up of angular silt-sized quartz and albite grains (Plate VII-4) and an occasional chlorite-muscovite book. Small cubes of pyrite up to 0.25 inch square are scattered throughout the limestones. The silt content varies from sample to sample. Calcite associated with silt in thin laminae is usually coarser grained than the bulk of the calcite in the rock. Evans (1961) commented that the pinkish limestones are coarser grained than the grey ones. This writer found this to be true for some groups of samples but not for others. The differences, if any, are slight.

(ii) Interbedded Slates and Siltstones - A sample of calcareous green slate from Member B_3 in the Meadow Creek Anticlinorium consists of about 30 percent medium crystalline calcite, 30 percent silt-sized grains of quartz and albite, and 30 percent muscovite and chlorite flakes. The remainder is books of chlorite up to 0.36 mm in diameter.

Northeastern Facies

In the vicinity of Old Fort Point in the Jasper Anticlinorium, the three fold sub-

division of Member B is not applicable. Instead the member consists of greenish-grey laminated slates with interbedded limestone-breccia and siltstone (Figure 3).

(i) Argillaceous Limestone-Breccias - These breccias are a very distinctive lithology and occur as lenses up to 100 feet thick that are scattered throughout the section. They comprise up to 20 percent of the member. The lenses extend laterally for 200 to 300 times their maximum thickness (Evans, 1961). Scour is observed at the base of some of the lenses. The limestone phenoclasts (Plates I-3 and 5, VII-1) are angular and range in size from less than 1 inch to several feet in the longest direction, but are rarely more than 3 inches thick. Orientation of the phenoclasts is highly variable. They consist of finely to very finely crystalline calcite and their color ranges from pinkish grey in the lower breccias to grey in the upper ones. The phenoclasts are petrographically identical to the limestones in Member B_3 of the southwestern facies. The matrix in the lower breccias consists of silt-sized quartz, chlorite, and books of chlorite and muscovite in a groundmass of finely crystalline calcite, chlorite, muscovite and siderite. The percentage of groundmass decreases in the upper breccias.

(ii) Slates - The slates are made up mainly of fine-grained muscovite and chlorite flakes. Chlorite-muscovite books and angular silt-sized quartz and albite grains make up 10 to 20 percent of the rock and are concentrated in brown weathering laminae. Siderite and calcite comprise 1 to 2 percent except near the limestone-breccias where the percentage of calcite increases.

(iii) Siltstones - The calcareous siltstone lenses, which make up about 10 percent

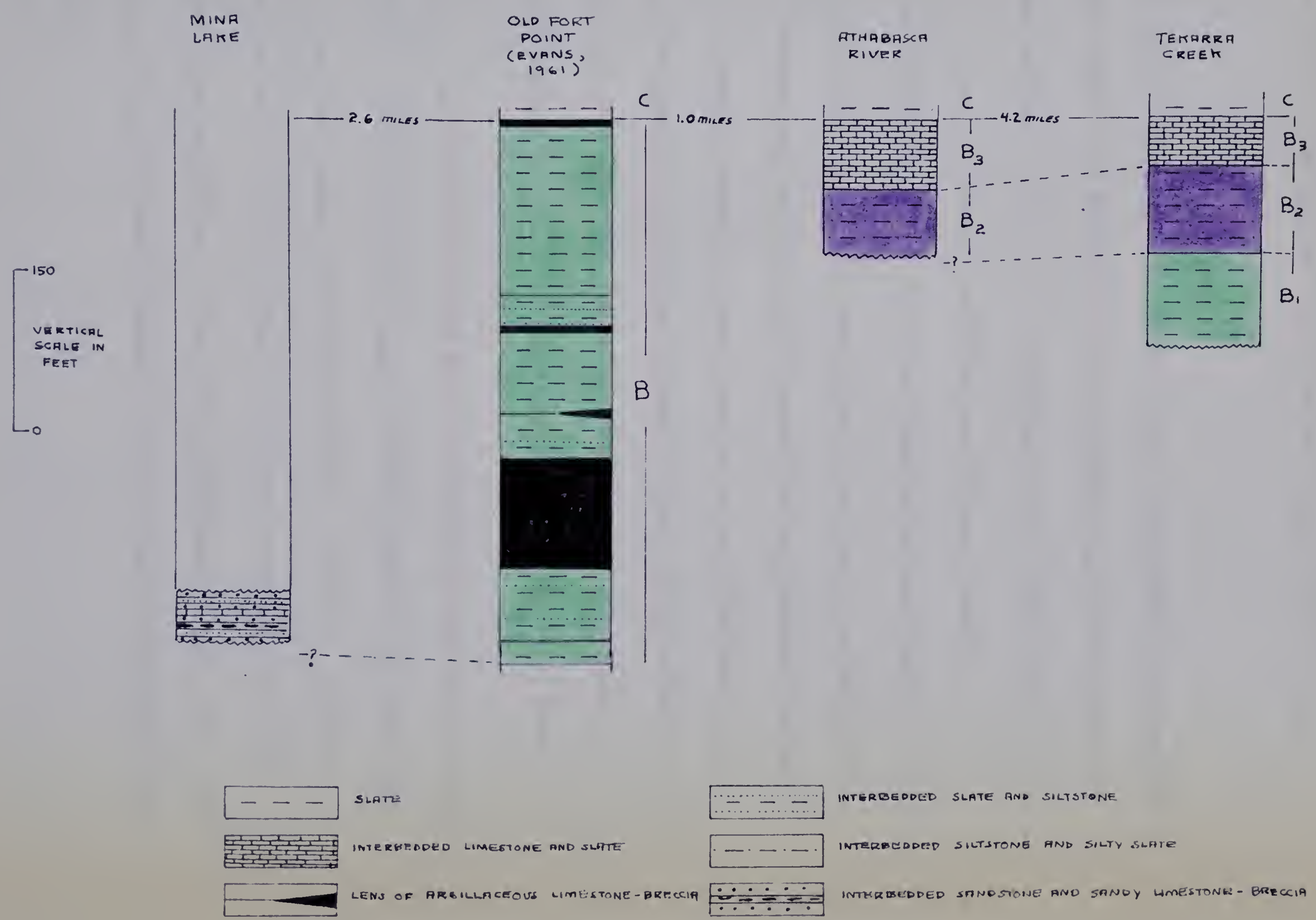
of the member near Old Fort Point, show cross-lamination and numerous scour, slump, and pinch and swell structures. The percentage of quartz and albite, in grains averaging 0.15 mm in diameter (Evans, 1961), increases from 50 at the base to 90 at the top of the section. The matrix of the siltstones consists mainly of calcite with very small flakes and larger books of chlorite and muscovite and minute rhombs of siderite. The matrix becomes progressively less abundant and more calcareous upwards.

(iv) Mina Lake Section - This small section is located in the northwestern part of the Jasper Anticlinorium (Figure 4), and was correlated by Evans (1961) with the lower portion of Member B exposed at Old Fort Point. At this locality the present writer has measured about 40 feet of interbedded tan colored fine-grained calcareous sandstones, tan to grey colored calcareous siltstones, thinly bedded finely crystalline red limestones, and intraformational limestone-breccias with red phenoclasts and a fine-grained sandy matrix. The fine-grained sandstones are composed largely of quartz grains in a matrix of crystalline calcite with little or no micaceous material (Plate VII-3). The sandstones are often well sorted. Sedimentary structures commonly observed in this section include small-scale scour channels, desiccation cracks in limestone beds, extensive cross-lamination, and the intraformational limestone-breccias mentioned previously. Sections similar to the one at Mina Lake have not been recognized elsewhere.

Correlation Between the Northeastern and Southwestern Facies of Member B

The occurrence of pink limestone phenoclasts near the base and grey near the top of the northeastern facies of Member B suggests that most if not all of this facies was being deposited while Member B_3 was being deposited to the southwest (Figure 3). The equivalents of Members B_1 and B_2 are therefore not represented in the northeastern facies

Figure 4 Stratigraphic Relationships and Terminology in Member B, Old Fort Point Formation, Jasper Anticlinorium



either because of erosion or non-deposition. The existence of a 5° angular discordance between Members A and B near Old Fort Point (Plate I-6) supports this conclusion.

Member C

One mile southeast of the bridge at Old Fort Point, Evans (1961) measured 250 feet of remarkably uniform, dark bluish-grey, rusty weathering slates. They overlie Member B and were designated Member C. The thickness of the member was found to vary considerably being only 90 feet on the hillside west of Jasper townsite. In the southern part of the anticlinorium, a single massive bed of arenaceous limestone-breccia was found near the top of Member C. The phenoclasts in the breccia are fragments of dark bluish-grey limestone beds and the matrix is coarse-grained calcareous sandstone. Evans (1961) was not certain whether this breccia marked the top of the bluish-grey slates or whether it was overlain by additional Member C slates. In all the sections examined by the present writer the breccia is overlain by the green and grey slates and siltstones of Member D, and therefore it appears that the breccia does mark the top of Member C.

In a number of sections the arenaceous limestone-breccia is underlain by several feet of alternating thin-bedded, dark bluish-grey limestones (similar to the phenoclasts in the arenaceous limestone-breccia), bluish-grey calcareous sandstones, and bluish-grey slates. The interbedded bluish-grey slates are similar to those that make up the bulk of the member in the Jasper area. In the following discussion, all the slates, limestones and sandstones will be included in Member C_1; the arenaceous limestone-breccia is designated as C_2.

The thickness of the easily recognized dark bluish-grey slates varies considerably. They are from 90 to 250 feet thick in the Jasper Anticlinorium but only 5 to 10 feet thick in the Portal Creek and Meadow Creek sections. In the Muhigan Creek Anticlinorium, only a few loose blocks of slate were found. The equivalent part of the section is not exposed at Yellowhead Lake. The interbedded limestones and sandstones at the top of C_1 are usually only a few feet thick at most localities except Tekarra Creek where 22 feet are exposed. The bedding in the limestones is commonly uneven and in places only concretions of limestone are found.

Slates. The dark bluish-grey slates usually weather to a rusty orange or brown color along cleavage surfaces. The sedimentary lamination is faintly visible and often disrupted by a well-developed slip or strain-slip cleavage (Plates VIII-4, IX-1 and IX-2). The slates are composed chiefly of muscovite and chlorite. Silt-sized particles of quartz and albite and chlorite-muscovite books up to 0.19 mm in diameter make up 5 to 15 percent of the rock. Siderite was not observed in the author's samples but Evans (1961) reported that some slates contain up to 5 percent siderite.

Limestones. The dark bluish-grey limestones consist almost entirely of aphanocrystalline calcite. The silt content of the phenoclasts ranges from 1 to 15 percent. Some small grains of siderite 0.02 mm in diameter are present and the limestones usually display abundant microfractures lined with calcite. The limestones appear to be identical to the majority of phenoclasts in the overlying arenaceous limestone-breccias of C_2.

Calcareous Sandstones. The dark bluish-grey sandstones are coarse grained; the larger sand grains are sub-rounded to rounded. Most of the grains are quartz and display undulose extinction. Partly replaced overgrowths (Plate VII-5)

are common on many of the smaller grains. The matrix of the sandstones, which often amounts to about 50 percent of the total rock, consists of finely to medium crystalline calcite. These sandstones appear to be more poorly sorted than the sandy matrix in the overlying arenaceous limestone-breccias.

Member C_2 is present in parts of the Jasper Anticlinorium and also in the Portal, Muhigan and Meadow Creek sections. The thickness of the arenaceous limestone-breccia ranges from a minimum of 1 foot to a maximum of 20 feet (Portal Creek section). The average thickness in the Meadow Creek Anticlinorium is about 3 feet. In the Muhigan Creek section, the arenaceous limestone-breccia grades upwards into calcareous sandstone.

Limestone Phenoclasts. Angular fragments of bedded limestones make up from 20 to 60 percent of the total rock (Plates VII-2 and II-3). The ratio of phenoclasts are usually randomly oriented throughout the breccia but folding has sometimes produced a marked preferred orientation (Plates II-5 and II-7). The phenoclasts to matrix varies widely within a single outcrop. The size of phenoclasts ranges from less than 0.5 inches to about 1 foot in length; maximum thickness is about 1.5 inches. Most of the phenoclasts are dark bluish-grey in color and consist largely of aphanocrystalline calcite with an average grain size of about 5 microns. Silt content ranges from 1 to 15 percent. As mentioned previously, these phenoclasts are identical in nature to the limestone beds of C_1 although some are grey in color (Plate II-3).

Matrix. The sand grains in the matrix (Plate VII-2) stand out sharply on weathered surfaces. They range in size from 0.25 to 2 mm in diameter and are largely quartz, either single or composite grains. The larger grains are rounded to well rounded. Many have overgrowths of quartz, and replacement of

quartz and feldspar grains by calcite is common. Some samples are moderately to well sorted; others are poorly sorted. The calcite cement is usually twinned and medium crystalline in size.

Member D

The type section of Member D is located about one-half mile northeast of Old Fort Point (Evans, 1961). In the Jasper Anticlinorium, it is about 150 feet thick and made up largely of silty to sandy greenish and bluish-grey slates which are coarser grained near the top of the member. The contact of Member D with the Wynd Formation is somewhat gradational in the Jasper Anticlinorium. In the Meadow Creek area, the percentage of silt beds in the upper part of the member is less and the contact abrupt but conformable (Plate I-1). Sections ranging from 175 to 275 feet in thickness were measured in the latterarea while the estimated thickness in the Muhigan Creek area is 160 feet. In the Portal Creek section, a very distinctive quartz pebble limestone-breccia is present about 60 feet above the base of the member.

Slates and Siltstones. Member D slates are usually well laminated and well cleaved. They are light greenish-grey on a fresh surface and weather to an olive grey color. Interbedded silty layers weather a dark yellowish-brown (Plate I-2). Thin sections from the Meadow Creek area show that the slates are made up of about 50 percent fine-grained muscovite and chlorite and 10 to 15 percent finely crystalline calcite scattered throughout the slate and concentrated into thin laminae. Angular silt grains of quartz and albite may comprise up to 50 percent of the rock in some cases. Chlorite-muscovite books and siderite grains make up the remaining few percent.

The silty laminae consist largely of well sorted silt-sized quartz and albite and finely crystalline calcite. Siderite is present in quantities of up to 5 percent.

Quartz-Pebble Limestone-Breccia. A sample of this unusual and restricted lithology is illustrated in Plate II-2. The only known occurrence of this rock-type is in the Portal Creek section where a 5-foot thick bed is exposed. Unfortunately, the contact of the breccia with the adjacent slates could not be observed. This breccia is noteworthy not only because of the rather unusual association of quartz pebbles and limestone phenoclasts but because some of the phenoclasts are derived from pre-existing arenaceous limestone-breccias similar to those of Member C_2.

(i) Phenoclasts - There are three types of phenoclasts in the quartz-pebble breccias. The most abundant type is of dark bluish-grey, micrite-type limestone similar to that in Members C_1 and C_2. The fragments which are angular are usually randomly oriented and up to 12 inches in length. The second most abundant type is of bluish-grey, coarse-grained, calcareous sandstone similar to that of Member C_1. The third type is of fragments of an arenaceous limestone-breccia very much like that in Member C_2. The latter two types of phenoclasts are angular to subangular and attain boulder size.

(ii) Matrix - The rounded to subrounded pebbles in the matrix are almost all quartz pebbles and are up to 25 mm in diameter. Metaquartzite (Plate VII-6) and vein quartz pebbles have been recognized. The cement consists of a mixture of very finely crystalline calcite with fine-grained muscovite, chlorite and some albite. The ratio of matrix to phenoclasts is about one to one.

Heavy Minerals in the Meadow Creek and Old Fort Point Formations

Heavy accessory minerals were separated from a number of samples of the Meadow Creek and Old Fort Point Formations. The suite present consists largely of the ultra-stable minerals zircon and tourmaline. In two of the samples, the

minerals were counted and the results are presented in Table 3.

Table 3. Heavy Accessory Mineral Suites

	PC-1 (1) %	MC-13 (2) %
Zircon	87	81
Tourmaline	9	18
Rutile	1	
Garnet	1	1
Sphene	1	
Anatase	1	

(1) Pebbly limestone-breccia from Old Fort Point Formation, Member D, Portal Creek Anticlinorium

(2) Medium to coarse-grained sandstone 40 feet below top of Meadow Creek Formation, Meadow Creek Anticlinorium

Apatite, which may have been present in the samples, would have been destroyed because it was found necessary to treat the samples with hydrochloric acid.

Most of the zircons are pale pink to dark purple hyacinths. Unzoned hyacinths are rounded to well-rounded; zoned ones are more euhedral. Overgrowths are extremely rare, but unoriented inclusions are common. Most of the tourmalines are well-rounded though some retain their original prismatic outline. Using the criteria established by Krynine (1946), most of the tourmalines appear to have been derived from granitic or metamorphic rocks, a smaller number derived from pegmatites.

Studies of heavy minerals in the Wynd and Jasper Formations yielded similar suites (e.g. Akehurst, 1964; and Bielenstein, 1964).

Conditions of Deposition of the Meadow Creek and Old Fort Formations

Meadow Creek Formation

The poorly sorted and very coarse nature of the Meadow Creek detritus suggests that it was deposited in a nonmarine environment or in a rapidly subsiding basin where wave action was of too short duration to cause winnowing of the sediments. The angularity of the sand-sized fraction suggests that the sedimentary materials had not been transported a great distance and may be first-cycle sediments.

The gross lithology of the limited section of the Meadow Creek Formation resembles that of the better exposed and more widely studied Wynd Formation. The latter formation has been interpreted to consist largely of deltaic sediments so it is not unreasonable to suspect that the Meadow Creek Formation was deposited in a similar environment. The sandstones and conglomerates were possibly deposited in or near stream channels, the finer slates and siltstones representing interchannel lagoon or bay deposits.

Old Fort Point Formation

That the Old Fort Point Formation was deposited in a marine environment is suggested by (1) the finely laminated nature of most of the slates, (2) the vertical and lateral continuity of the different members, and (3) the widespread distribution of limestones. An alternative explanation is that the formation was deposited in a large lake. In view of the fact that some Old Fort Point lithologies can be traced as far south as the Lake Louise area, a lacustrine origin is considered unlikely.

That the water was shallow during deposition of the Old Fort Point is indicated by the intraformational limestone-breccias, desiccation cracks in limestone beds, cross-lamination, and ripple marks. The existence of a shoreline to the northeast is indicated by the coarsening of most members towards the northeast,

the presence of argillaceous limestone-breccias and a quartz-pebble limestone-breccia in the east, and the attitude of cross-lamination.

Member A. The abrupt change from the pebbly sandstones of the Meadow Creek Formation to the finely laminated dark bluish-grey slates of Member A may reflect a change to deeper water sedimentation at some distance from the shoreline. The relative location of the shoreline is indicated by the decrease in the proportion of siltstone in Member A from east to west and by the attitude of cross-lamination in the siltstones. A westward decrease in the amount of siltstone appears to be characteristic of most of the Old Fort Point Formation. The siltstone beds at the top of the member probably record a shallowing of the sea.

Member B. The shallowing trend evident in the upper part of Member A appears to have continued through the deposition of both the northeastern and southwestern facies of Member B. The water probably was shallowest during the deposition of the interbedded limestones and slates, and their equivalents the interbedded slates, siltstones and argillaceous limestone-breccia.

(i) Southwestern Facies - The fine-grained and finely laminated muds of Member B_1 were probably deposited in deeper and quieter waters than the overlying very silty slates and siltstones of Member B_2. When the purple beds of Member B_2 were being deposited the environment must not have been reducing in nature or the detrital magnetite would have been removed and the strata would no longer have their source of red pigment. The microcrystalline oozes of Member B_3 probably formed by rapid chemical precipitation in sea water (Folk, 1962, p. 66). The fine-grained carbonate settled to the bottom and in some cases was probably drifted about by weak currents. At the time of limestone formation, only minor amounts of silt were being received; the silt present in the limestone often exhibits cross-lamination. The small-scale ripple marks in the limestones in the Meadow Creek

area suggest they were deposited under shallow water conditions.

That the water probably shallowed towards the northeast is evidenced by the incipient brecciation (Plate II-4) and desiccation cracks found in the upper limestone beds of the Tekarra Creek and Athabasca River sections. These two sections are the exposures of the southwest facies nearest to the outcrops of the northeastern facies.

(ii) Northeastern Facies - Non-deposition or erosion may account for the absence of Member B_1 and B_2 in the northeastern facies near Old Fort Point. That Member B in the northeastern facies was deposited in shallower waters than Member B_3 of the southwestern facies is indicated by (1) the presence of the argillaceous limestone-breccias and (2) the greater proportion of silt-sized material in the northeastern facies. The upwards increase in the silt-sized fraction in the northeastern facies may indicate an overall shallowing during this time.

The argillaceous limestone-breccias were formed from alternating silts, calcareous muds and bedded micrite limestones. At numerous times during the deposition of Member B, there were temporary lowerings of the sea level which, in the general area of the Old Fort Point, exposed pan-like areas of limestones to the air. During these periods of exposure the limestone beds were lithified and in some cases desiccation cracks developed. These lithified and cracked beds of limestone were later disrupted either by the flooding of the pans and/or by intense wave action during storms when the limestones were at a shallow depth. The fragments of limestone were moved about and surrounded by the unlithified muds and silts which may have behaved like thixotropic substances. Fragments of lithified mud or siltstone are not found in the breccias. Basal scour suggests that some downslope movement of phenoclasts and matrix may have occurred (this would have aided in the formation of the breccias) but the limited development of the

breccias and the fact that none of the breccias are found to overlie bedded limestone indicates that downslope movement was probably not a prime factor in the development of the breccias. The angularity of the fragments also suggests they were not moved far.

Member C. The uniform fine-grained argillaceous nature of the bluish-grey slates of Member C suggests a return to deeper water and quieter conditions of deposition. The great thickness variations, 10 feet thick at Meadow Creek and 300 feet thick at Old Fort Point, may have been caused by a change in the pattern of the streams transporting the muds.

That the water shallowed toward the end of the deposition of Member C_1 is indicated by the coarser sediments in the form of rounded quartzose sands that occur near the top of the member. These influxes of sand, which were sorted by the winnowing action of waves and currents, alternated with periods of deposition of microcrystalline carbonate ooze that comprises the dark bluish-grey limestones. The phenoclasts of the overlying blanket-like arenaceous limestone-breccia of Member C_2 are locally derived from the limestone beds of Member C_1. The sand grains of the matrix were either derived from underlying sandstones or washed in from outside the area. The breccias probably formed in a manner somewhat similar to that described for the argillaceous limestone-breccias. The more widespread nature of the arenaceous limestone-breccia indicates that the water was shallower over a broader area than when the Member B breccias were formed.

Member D. Following formation of the arenaceous limestone-breccias of Member C_2, the fine-grained muds of Member D were laid down, perhaps largely in a deeper and quieter water environment. That shallowing occurred near the end of the deposition of Member D is indicated by the increase in siltstone toward the top.

The quartz-pebble limestone-breccia in the Portal Creek section is difficult to explain. The nature of the breccia requires that Members C_1 and C_2 were exposed to erosion. The pebbles in the matrix were transported in from outside the area. The size of the pebbles and phenoclasts indicates that they were transported in a high energy medium. The apparent localized nature of the breccia suggests that it might be a channel fill deposit. If this is so then the water must not have been very deep in the Portal Creek area at this time. The stream that occupied the channel carried pebbles from the source terrain farther east, and more locally had eroded the poorly lithified beds of Members C_1 and C_2. Normal faulting, a not uncommon phenomenon in recent deltas, may have exposed the older breccias in cliffs. A less tentative explanation awaits the discovery of additional sections where the contacts of the quartz pebble limestone-breccia can be observed.

The deposition of the argillaceous Old Fort Point Formation was terminated with the first influx of coarse detritus of the advancing Wynd Formation deltas.

Provenance

Measurements of cross-bedding in the Gog and Miette Groups of Banff and Jasper National Parks indicate that the source terrain of the sedimentary materials was located to the east and northeast (Hughes, 1953; Charlesworth et al., 1961; and Mountjoy and Aitken, 1963). Although cross-lamination in the Old Fort Point is on too small a scale to measure, most examples indicate a movement of sediments from east to west. Stratigraphic relationships support the cross-bedding evidence: The Old Fort Point Formation becomes finer grained towards the west as do the overlying Wynd Formation (Charlesworth, personal communication) and the Gog Group (Mountjoy and Aitken, 1963).

The source terrain must have been the Precambrian shield or its extension

under the Western Canada Sedimentary Basin. The Old Fort Point and Meadow Creek Formations contain detritus derived from plutonic, pegmatitic, metamorphic and sedimentary rocks. Studies of the basement under the Western Canada Sedimentary Basin (Burwash et al., 1964) indicate the presence of the above listed rock types. Although the angularity and textural immaturity of much of the Meadow Creek and Wynd Formations suggest that they are first cycle sediments, the presence in the Old Fort Point Formation of well-rounded quartz grains with overgrowths indicates that some of the detritus had passed through at least two sedimentary cycles. The well-rounded nature of zircons in the heavy mineral suites also leads one to the same conclusion.

The absence of potassic and calcic feldspars in the Old Fort Point Formation can be attributed either to their destruction during weathering and transportation or to their destruction or alteration during metamorphism. In spite of the general lack of petrographic evidence indicating destruction or alteration, the absence of potassic and calcic feldspars from the Meadow Creek, Old Fort Point and most of the Wynd Formation suggests that their absence is related to the metamorphism.

Potassium-argon dating of the basement and exposed shield in Western Canada has yielded numerous dates in the 1600 to 1900 million year range (Burwash et al., 1964). Detrital muscovite flakes from the Wynd Formation have also yielded potassium-argon dates as old as 1775 million years (Steiner, 1962), indicating that the shield or its extension was the source of the clastics.

The change from fine to very coarse clastics at the Old Fort Point - Wynd contact may be due to a number of factors or a combination of factors - (1) a change in climate in the source terrain, (2) relative uplift in the source terrain (perhaps by faulting), and (3) a major change in the pattern of the river systems supplying the detritus. If it were possible to trace the Old Fort Point farther east, it might be

found that the formation graded laterally into Wynd type coarse clastics.

Age and Correlation

The Meadow Creek and Old Fort Point Formations are most likely Late Precambrian (Proterozoic) in age (Table 1). Mountjoy (1962) reported that Archaeocyathids and Scolithus tubes occur in the upper 1000 feet of the Gog Group, about 5000 to 6000 feet above the top of the Old Fort Point Formation. Charlesworth et al., (1963) provisionally drew the Cambrian-Precambrian boundary at the base of the Gog Group, including the Miette Group in the Precambrian. Mountjoy (ibid.) also considers the Miette Group to be Precambrian.

Hughes (1953) stated that there are about 6000 feet of Precambrian shales and some interbedded sandstones in the Sunwapta Pass area, about 60 miles south of Jasper townsite. These are probably the equivalents of the Miette Group and are overlain by about 5000 feet of quartzites which resemble the Gog Group. His descriptions of the lower part of the section are not detailed enough to allow recognition of any possible Old Fort Point beds.

Charlesworth et al., (1961, p. 10) stated "the Old Fort Point Formation is lithologically similar to the lower part of the Bow Valley Hector Formation (Walcott, 1910, p. 428) which contains green and purple argillites, siltstones, limestone-breccias and quartzose limestone-breccias." The writer has not visited the Bow Valley section, but has examined samples collected from there by Charlesworth. They show marked similarities to the rocks of the Old Fort Point Formation. Additional field work will have to be done between Jasper and the Bow River before more definite correlations can be made.

Brief Summary of Conclusions

The Late Precambrian Old Fort Point Formation, appears to record sedimentation in a shallow water marine environment. The vertical variations within the formation show evidence for three minor transgressive and regressive cycles. Member A was deposited, at least initially, in deeper water than the underlying Meadow Creek Formation. A gradual shallowing occurred toward the top of Member A and continued through the deposition of Member B. The second cycle began with the deposition of the uniform muds of Member C in deeper water than the Member B beds. A shallowing occurred toward the top of Member C and culminated in the widespread formation of the arenaceous limestone-breccia. The third cycle began with the deepening of the water associated with the deposition of Member D and culminated in the shallower water conditions which prevailed during the deposition of the overlying coarse clastics of the Wynd Formation.

Lateral variations and sedimentary structures within the Old Fort Point Formation (Figure 3) indicate that the shoreline was located to the northeast. The source of the sediments was the igneous, metamorphic and sedimentary terrain of the Precambrian shield and its extension under the Western Canada Sedimentary Basin. The source terrain was probably very low lying for most all of Old Fort Point time. This is suggested by the very fine-grained nature of most of the formation, even though the water was very shallow at the time of deposition.

CHAPTER 3 - TECTONICS

Regional Structural Setting

The central Alberta Rocky Mountains around Jasper consist of largely unmetamorphosed sedimentary rocks lying in large, southwesterly dipping imbricate thrust sheets (Figure 5). Rocks within the thrust sheets, and most of the faults themselves, are generally folded. The amount of shortening that has occured in the area is not known but estimates for other parts of the Canadian Rocky Mountains range from 60 to over 100 miles (Shaw, 1963). The westward dipping crystalline basement underneath the ranges does not appear in any of them and presumably was not deformed to any great extent during the building of the Canadian Rockies (Charlesworth, 1959).

Bordered on the east by the relatively undeformed sedimentary strata of the Interior Plains and on the west by the igneous and metamorphic rocks of the Western Cordillera, the central Alberta Rockies can be divided into three regions of differing tectonic style. From east to west the regions are: (1) the Foothills, (2) the Eastern (Front) Ranges, and (3) the Main Ranges (Figure 5). Within these divisions, the 25,000 to 35,000 foot thick stratigraphic sequence has been disrupted by eight to ten parallel thrusts. The thrusts are splays off three pronounced zones of décollement: Proterozoic under the Main Ranges, Cambrian under the Eastern Ranges, and Upper Paleozoic under the Foothills. Thrusting probably was initiated in the southwest, younger thrusts originating beneath and to the northeast of older ones (Mountjoy, 1962).

The Foothills, separated from the Eastern Ranges to the west by the Rocky Pass and Miette thrusts (Figures 5 and 6), are composed of moderately to complexly folded

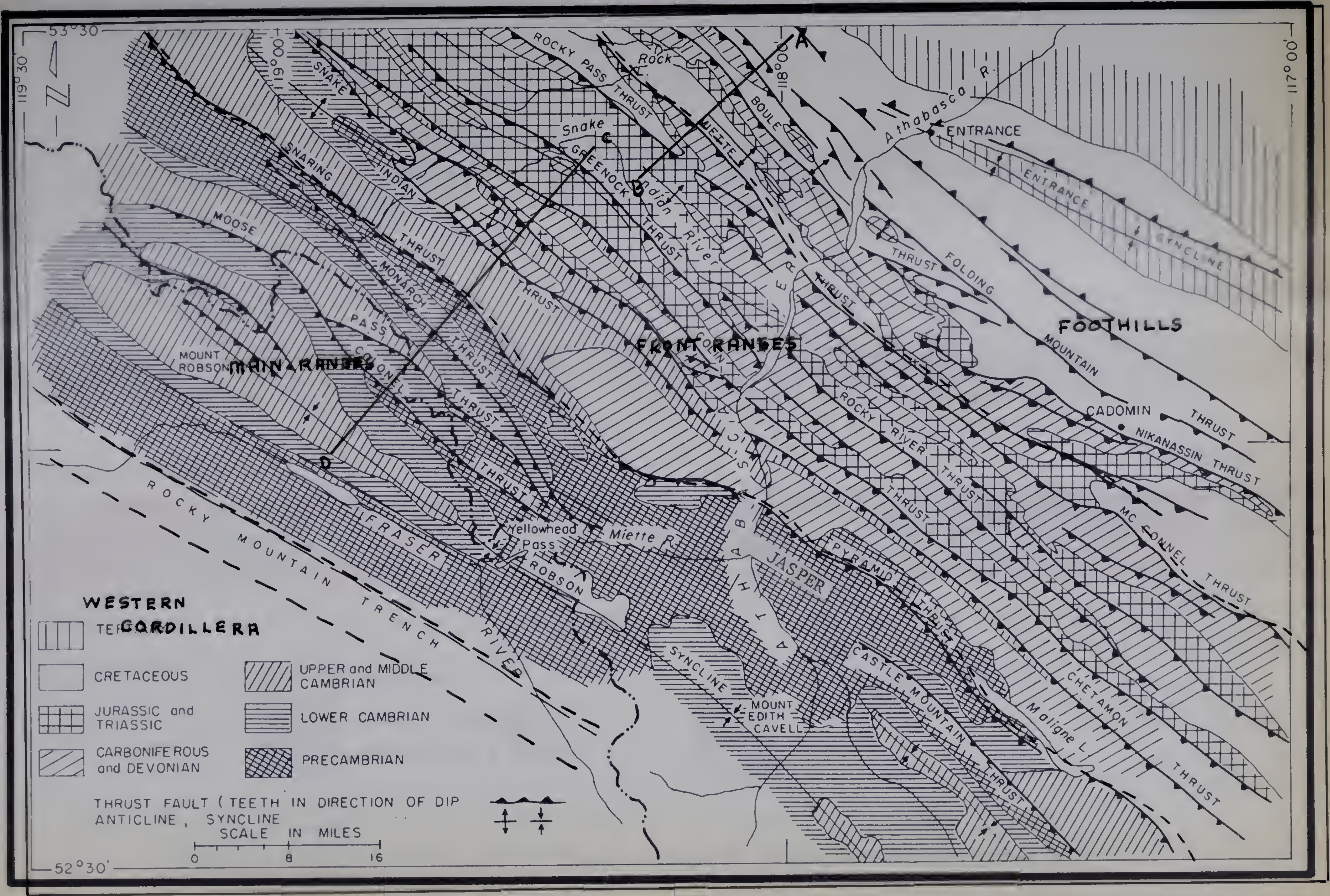
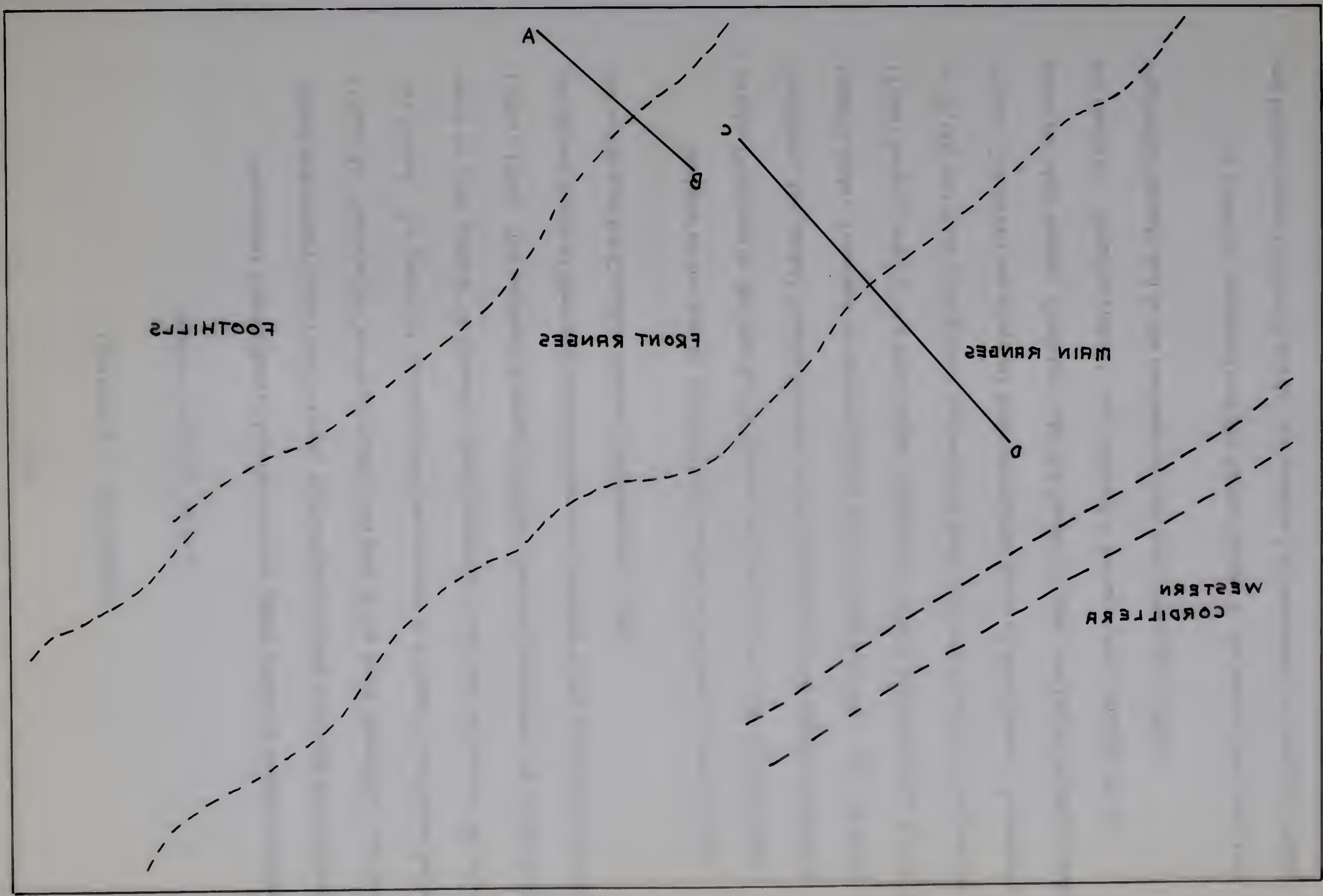


FIG. 5 REGIONAL STRUCTURE OF THE CENTRAL ALBERTA ROCKY MOUNTAINS AROUND JASPER (modified from MOUNTJOY, 1961)


A
B
C
D
FOOTHILLS
FRONT RANGES
MAIN RANGES
WESTERN
CORDILLERA

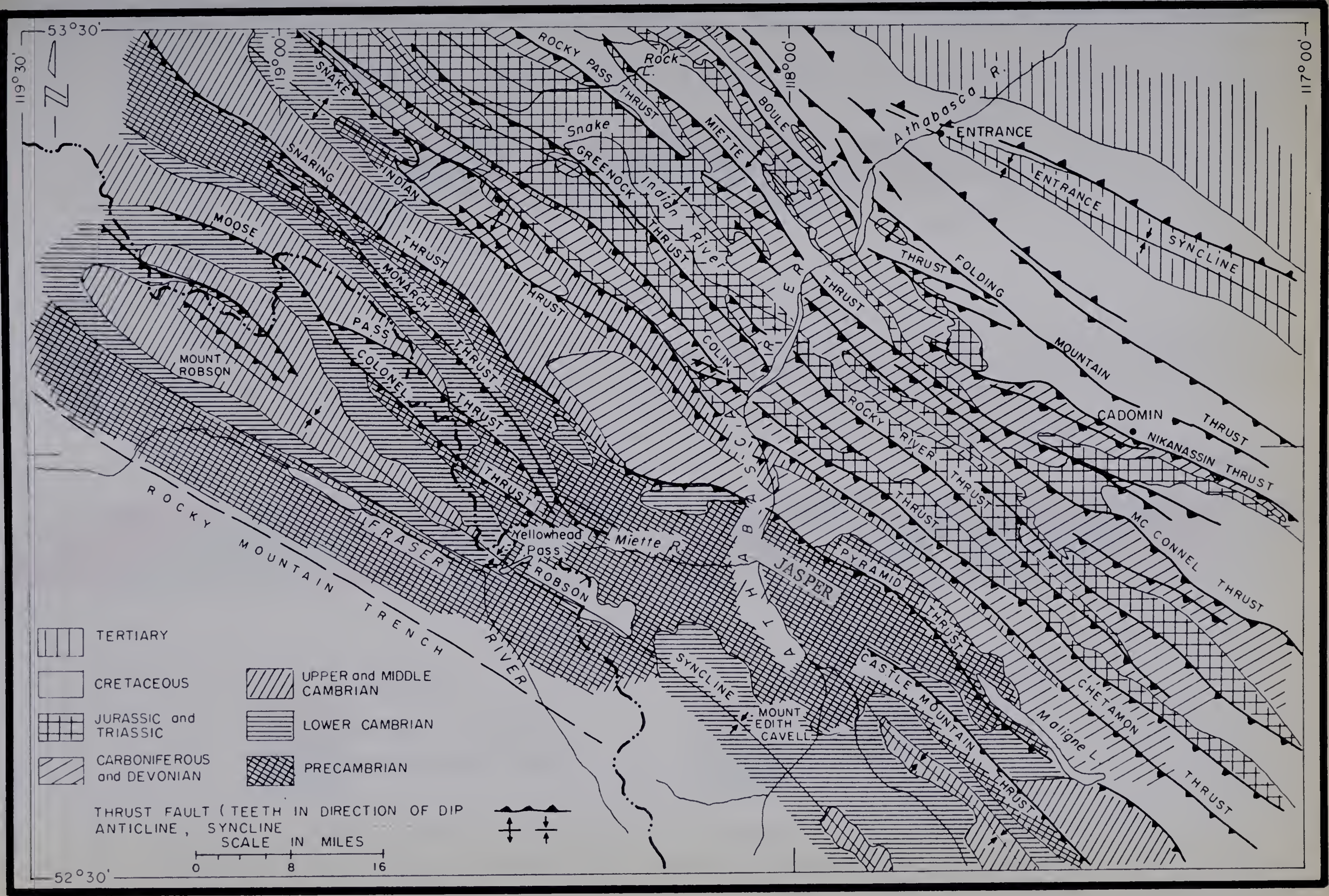


FIG. 5 REGIONAL STRUCTURE OF THE CENTRAL ALBERTA ROCKY MOUNTAINS AROUND JASPER (modified from MOUNTJOY, 1961)

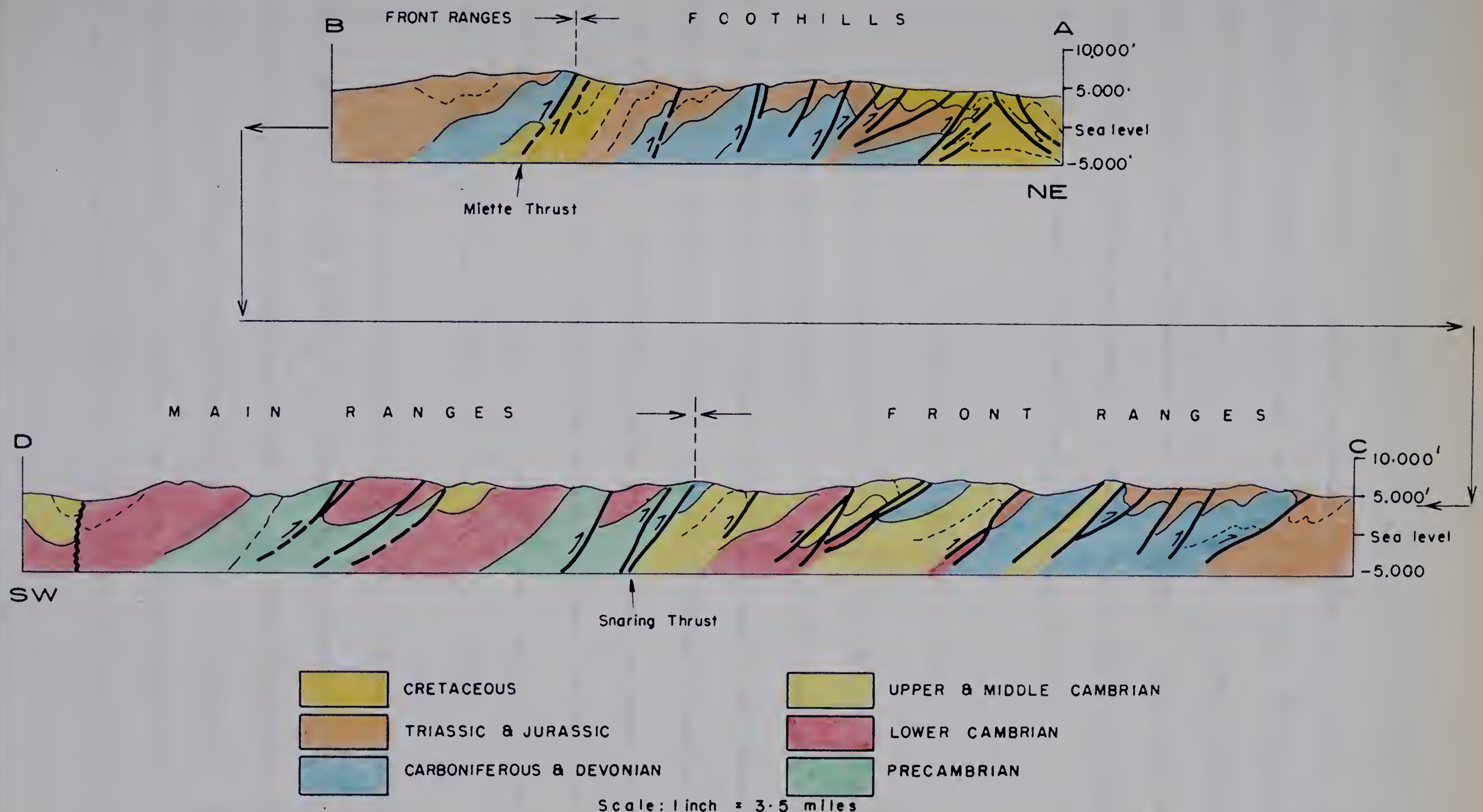


FIG. 6 STRUCTURAL CROSS-SECTIONS THROUGH CENTRAL ALBERTA ROCKY MOUNTAINS AROUND JASPER *(Modified from MOUNTJOY, 1963)*

For location of sections consult Figure 5

and faulted Upper Paleozoic to Upper Cretaceous strata (Mountjoy, 1962). Structurally simpler than the Foothills, the Eastern Ranges can be divided into a number of southwesterly dipping thrust sheets containing Cambrian to Jurassic rocks. The Pyramid and Snaring thrusts separate the Eastern Ranges from the Main Ranges. The latter are made up predominantly of folded and faulted Proterozoic and Lower Paleozoic rocks and are bounded on the west by the Rocky Mountain Trench. At the latitude of Jasper, the Foothills, Eastern and Main Ranges are about 40, 35 and 45 miles wide respectively.

Structure of the Pyramid Thrust Sheet

The Pyramid thrust crosses the Athabasca River Valley about two and one-half miles northeast of Jasper townsite (Figure 1). It strikes N 60° W and dips southwest at 70° near the Athabasca River but flattens to a gentle westward dip on Pyramid Mountain (Akehurst, 1964). Stratigraphic throw here is about 10,000 feet; Devonian to Mississippian rocks crop out in the footwall, whereas the Early Cambrian Jasper Formation occurs in the hanging wall. About 8 miles northwest of Jasper, the thrust dies out in Cambrian strata. The Snaring thrust, which lies to the northwest of the Pyramid thrust (Figure 5), is thought to be related to the latter (Mountjoy, 1962).

The competent sandstones and quartzites of the Gog Group are deformed into broad, simple upright folds (Figure 1). In contrast, the relatively incompetent shales and sandstones of the underlying Miette Group are more tightly folded into a series of anticlinoria and synclinoria with northwest-southeast striking axial surfaces. Within the Wynd Formation folds are usually upright, whereas in the underlying Old Fort Point they are usually overturned toward the northeast. This variation in style within the Proterozoic

and Lower Cambrian of the Main Ranges is summarized in Table 4. Evidence of low-grade metamorphism, such as slaty cleavage, becomes more pronounced as the base of the Miette Group is approached.

General Geology of the Meadow Creek Anticlinorium

Location, Exposures and Field Methods

A nine-square-mile area astride the Meadow Creek Anticlinorium and underlain by the Meadow Creek, Old Fort Point and Wynd Formations was selected for detailed structural study. The exposures are poor except along the railway, the highway and Meadow Creek (Figure 1). Plate III-1 illustrates the typical topography of the area.

Aerial photographs, enlarged to a scale of about 4-inches-to-1-mile were used for mapping in the field. Base maps consisting of parts of the National Topographic 1:50,000 Series were enlarged to the same scale. When outcrops could not be located on the photographs, or where they were too closely spaced, compass and pace traverses were made.

Structural Subdivisions (Figure 7)

Northeast Limb This limb is essentially an overturned series of lower Wynd strata whose average strike and dip is N 49° W and 56° SW overturned (Figure 8). The limb is approximately 2000 feet wide and the structural relief is greater than 5000 feet. Measurements by Steiner (1962) and Bielenstein (1964) indicate that in this area competent arenaceous units make up more than 50 percent of the Wynd Formation. Folding within the limb is confined to a few, small closely spaced folds (50 feet between hinge zones).

TABLE 4: Variations in Nature of Folds in Lower Cambrian and Proterozoic Strata Near Jasper

	FORMATION		LITHOLOGY AND THICKNESS	NATURE OF FOLDS	
Lower Cambrian	Cavell Jasper		Competent Quartzits and Sandstones 4500'	Open Upright Folds	Decrease in "Wavelength"
?					
Proterozoic	Wynd	Upper Member	Incompetent Slates and Argillites 1600'	Open to Close Upright or Nearly Upright Folds	
		Lower Member	Alternating Incompetent Slates and Competent Arenites 2500'		
	Old Fort Point		Incompetent Slates 1200'	Tight Overturned Folds	
	Meadow Creek		Alternating Incompetent Slates and Competent Arenites 125'	?	

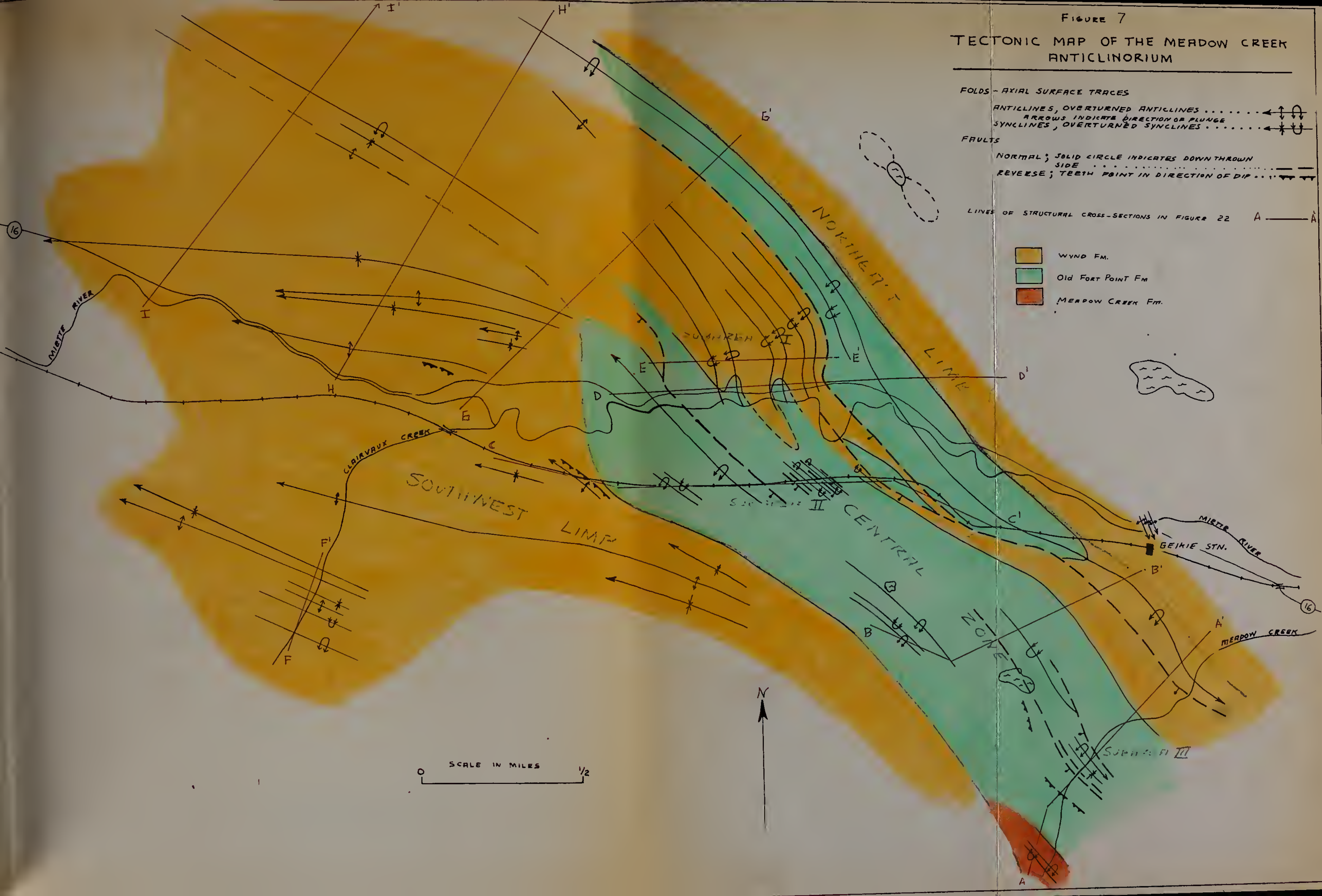


Figure 7
TECTONIC MAP OF THE MEADOW CREEK ANTICLINORIUM

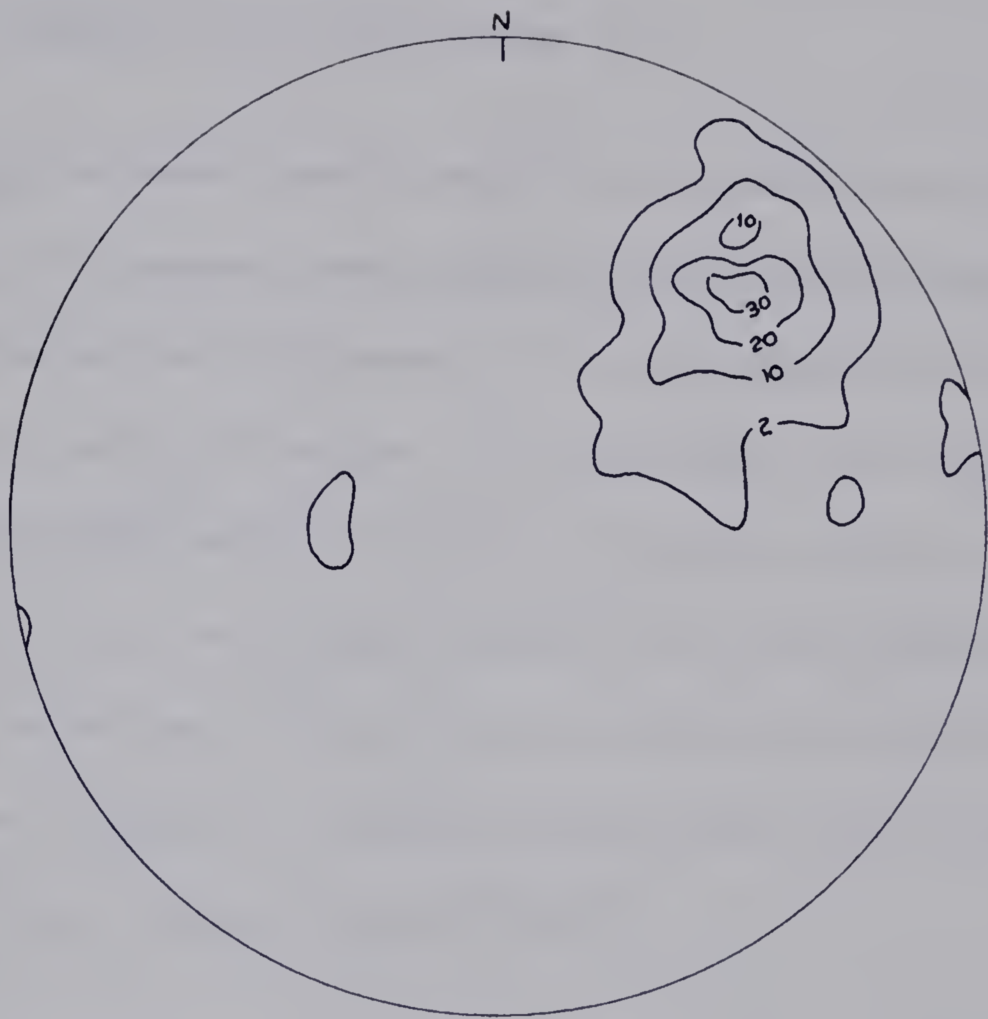


Figure 8 Contoured equal-area projection showing the distribution of poles to 52 S_2 planes in the overturned limb of the Meadow Creek Anticlinorium. Contours in percentage of poles per 1 percent of area.

The axial surface trace of the Minaga Creek Synclinorium is located one-half mile northeast of the map-area (Figure 1). The trend of this structure generally parallels that of the Meadow Creek Anticlinorium, varying from N 70° W in the southeast to N 50° W in the northwest (Charlesworth et al., 1961). It plunges northwest and rocks of the upper Wynd Formation crop out along Minaga Creek.

Central Zone The central zone (Figure 7) varies in width from one-half to one mile and consists of a northeast-southwest trending belt of asymmetrical close to tight folds which are overturned towards the northeast. The rocks exposed belong to the Meadow Creek, Old Fort Point and Wynd Formations. The axial surfaces of the folds in the Old Fort Point strike N 40°-50°W and dip 30°-50° SW. Although the direction of plunge of fold axes is variable, folds in the southeastern portion of the central zone generally plunge southeast, whereas those in the northwestern portion plunge toward the northwest. Several normal faults strike parallel to bedding and the structural trend of the anticlinorium, and dip southwest at angles of about 50° to 60°.

Southwest Limb The southwest limb of the anticlinorium can be divided into an area of southwest dipping Wynd strata, bounded to the southwest by an area of Wynd rocks in a series of westward-plunging, upright folds, whose axial surfaces strike obliquely to the axial surfaces in the central zone.

Folding

Introduction

The terms used to describe the geometry, attitude and style of folds are defined in Turner and Weiss (1963), Fleuty (1964) and McIntyre (1950). For purposes of brevity

and simplicity, the notation illustrated in Figure 9 has been adopted.

Methods of Analysis   Pi-diagrams and beta-diagrams were used extensively to determine the geometry, symmetry and orientation of folds. The advantages and disadvantages of these two methods are described in Ramsay (1964). Beta-axis determinations were arrived at by using a digital computer (see Appendix B) or by plotting intersections by hand on an equal-area net. Pi-diagrams were prepared by contouring point density distribution diagrams of poles to S_1 and then selecting a great circle which appeared to best-fit the density distributions.

Description of Folds in Meadow Creek Anticlinorium

Physical dimensions of the folds and the orientation of their component parts are summarized in Table 5. Most folds cannot be described in terms of wavelength and amplitude because they are asymmetrical. Substitute dimensions, such as the structural relief of folds and the horizontal distance between adjacent folds are used instead. In the following discussion, the lengths of the short and long limbs of folds are given as recommended by Fleuty (1964, p. 468).

Folds in Northeast Limb   Except for a few small folds seen along the Yellowhead Highway (Figure 10, in pocket) folds on the macroscopic scale (Turner and Weiss, 1963, p. 15) were not recognized in the mapping of the northeast limb.

Folds in the Central Zone   The central zone has been divided into three subareas (Figure 7).

(i) Physical Dimensions of Folds - The horizontal distance between the hinge zones of adjacent anticlines and synclines ranges from 80 to 650 feet (Table 5 and

Figure 9: Megascopic Planar and Linear Structures in the Precambrian Rocks of the Jasper area.

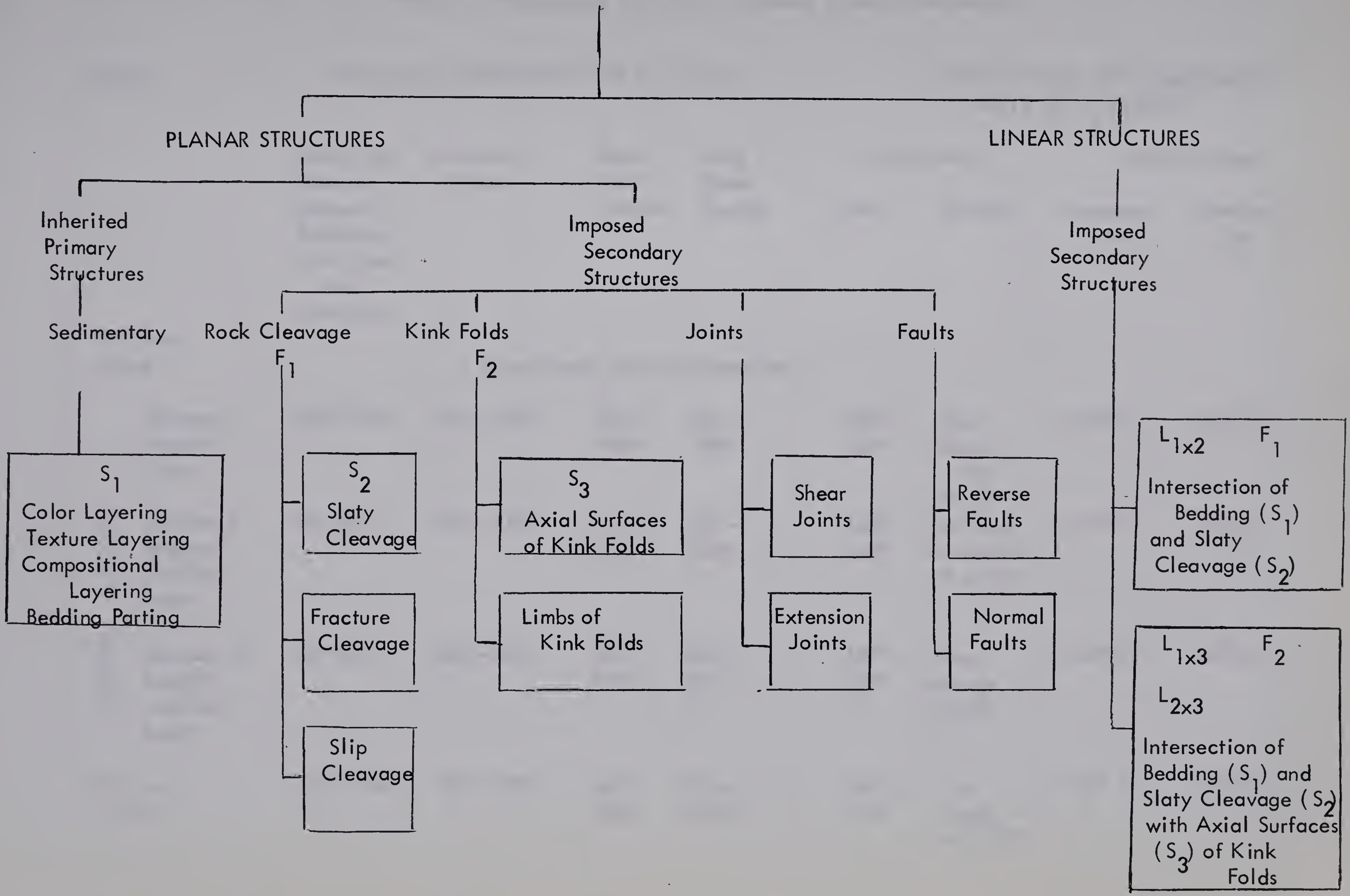


TABLE 5: Macroscopic F_1 Folds in Meadow Creek Anticlinorium

AREA	PHYSICAL DIMENSIONS OF F_1 FOLDS				ORIENTATION OF COMPONENT PARTS OF F_1 FOLDS			
					Fold Axes B_1		Axial Surfaces	
	Horizontal Distance Between Adjacent Anticlines and Synclines	Structural Relief	Short Limb Lengths	Long Limb Lengths	Trend	Plunge	Average Strike	Average Dip
NE Limb Wynd	Macroscopic folds not observed							
CENTRAL ZONE								
Subarea I largely Wynd	280'-600'	150'-1000'	200'-1000'	400' 1400'	130°-150°	Most plunge NW 10°-30°	N 40°W	60°SW
Subarea II largely Old Fort Point	80'-650'	100'-1000'	100'-400'	100'-1000'	130°-140°	NW and SE plunges 0° to 20°	N 40° W	50°SW
Subarea III largely Old Fort Point	80'-250'	200'-800'	100'-400'	400'-800'	125°-150°	Most plunge SE 0°-25°	N 40° W	40°SW
SW Limb Wynd	100'-1100'	150'-1000'	100'-1200'	100'-1600'	100°-110°	All plunge W 10°-35°	N 65° W	70°SW

Figures 7 and 10). The average distance is greater in the Wynd Formation than in the Old Fort Point Formation.

Structural relief varies from less than 100 feet in the smaller Old Fort Point folds to more than 1000 feet in the larger ones. Short limb lengths range from perhaps 50 feet to more than 1000 feet, whereas lengths of long limbs range from 100 feet to more than 1400 feet. Tracing individual folds along strike is difficult because of the paucity of exposures. One fold in the Old Fort Point can be traced for three and one-half miles. Many of the other folds are undoubtedly not so continuous.

(ii) Orientation of Component Parts of Folds - All the folds mapped in the central zone are overturned toward the northeast. The northeast limbs of anticlines are attenuated and therefore the folds are bilaterally asymmetrical. Average dips of the limbs of the folds are tabulated below in Table 6. Based on their interlimb angles the folds can be described as "close" to "tight" (Figure 11).

TABLE 6: Average Dip of Fold Limbs in the Central Zone

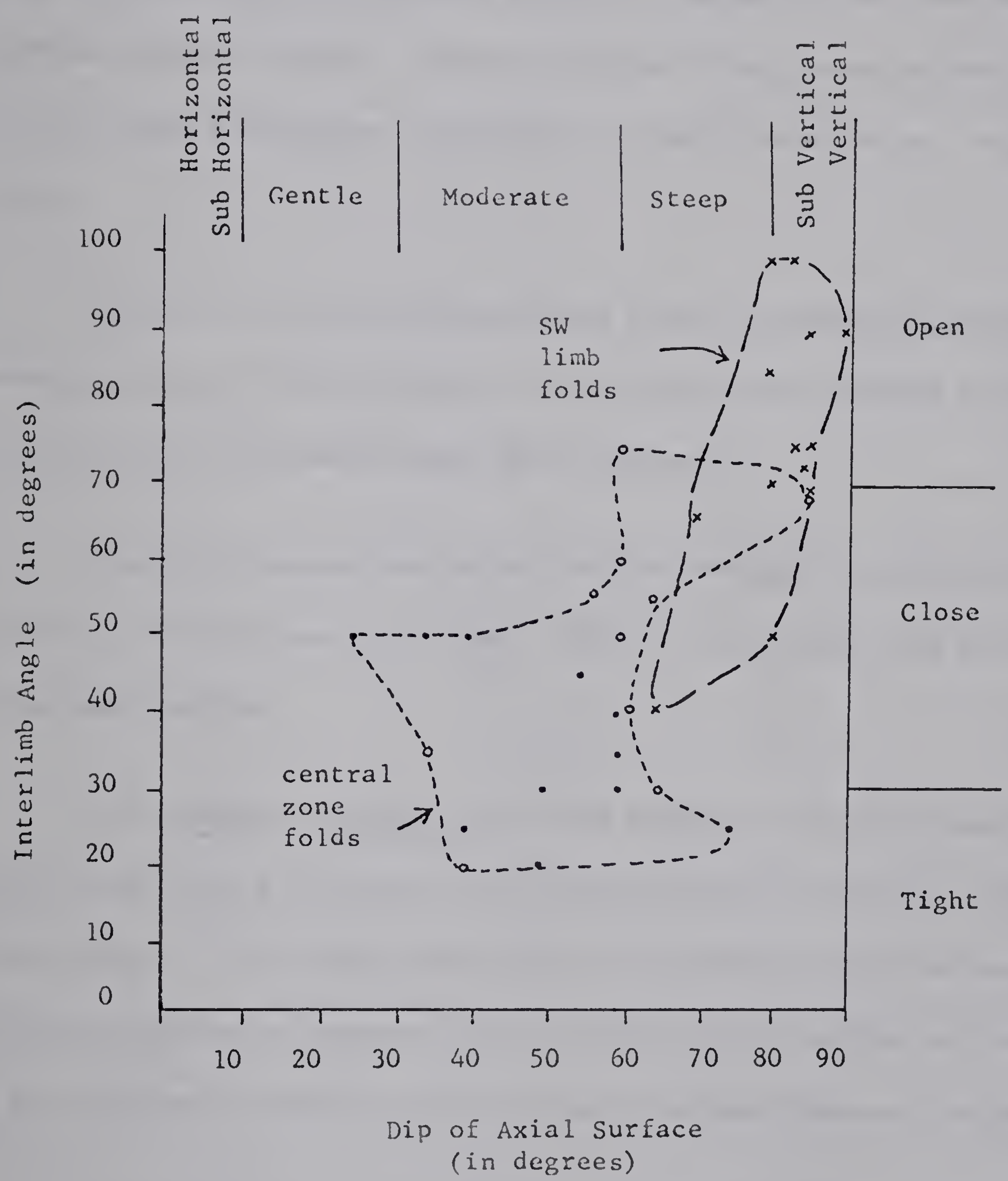
	Overturned NE limbs of Anticlines and SW limbs of Synclines	Normal SW dipping limbs
Subarea I	65° SW	57° SW
Subarea II	59° SW	31° SW
Subarea III	57° SW	23° SW*

* unreliable; insufficient data

The trend and plunges of fold axes, determined from pi- and beta-diagrams and

Figure 11

Variation of Interlimb Angle and Dip of Axial Surfaces for Macroscopic Folds in Central Zone and SW Limb - Folded Belt of Meadow Creek Anticlinorium



LEGEND

Central Zone — • Old Fort Point — o Wynd Formation

SW Limb - Folded Belt — x Wynd Formation

Classification after Fleuty (1964)

from cleavage-bedding intersections, are depicted in Figures 12, 13 and 14 and in Table 5. The trend of fold axes varies between 125° and 180° but most fall in the 125° to 150° range. Outcrop patterns and plots of bedding (S_1) poles (Figures 15 and 16) suggest a northwest plunge in Subarea I, whereas in Subarea III they plunge southeast. In Subarea II, folds plunge both northwest and southeast. Most fold axes plunge in the 0° to 30° range.

The strike of the axial surfaces of folds is fairly consistent throughout the central zone and averages N 40° W (Table 5). Dips are towards the southwest and decrease from about 60° in Subarea I to about 40° in Subarea III.

Overturning becomes more pronounced from northwest to southeast as the dip of the overturned limbs becomes less steep. The dip of the "normal" limbs also decreases in the same direction.

(iii) Geometric Classification - In the central zone the near linearity of axial surface traces (Figure 10) suggests that the axial surfaces of macroscopic folds are approximately planar. On the other hand, changes in the attitude of axial surfaces, e.g. the decrease in dip from the northwest to the southeast, indicate that they may be curviplanar or even nonplanar. Most mesoscopic folds appear to have planar axial surfaces.

Figures 17a, b and c are pi-diagrams of segments of individual overturned macroscopic folds from the central zone. About all that can be concluded from these plots is that some of the folds may approximate the condition of being plane cylindrical. Poles to S_1 for all the Wynd and Old Fort Point outcrops in the three subareas are plotted in Figures 15, 16, 18, and 19. The results are similar to those obtained for the individual

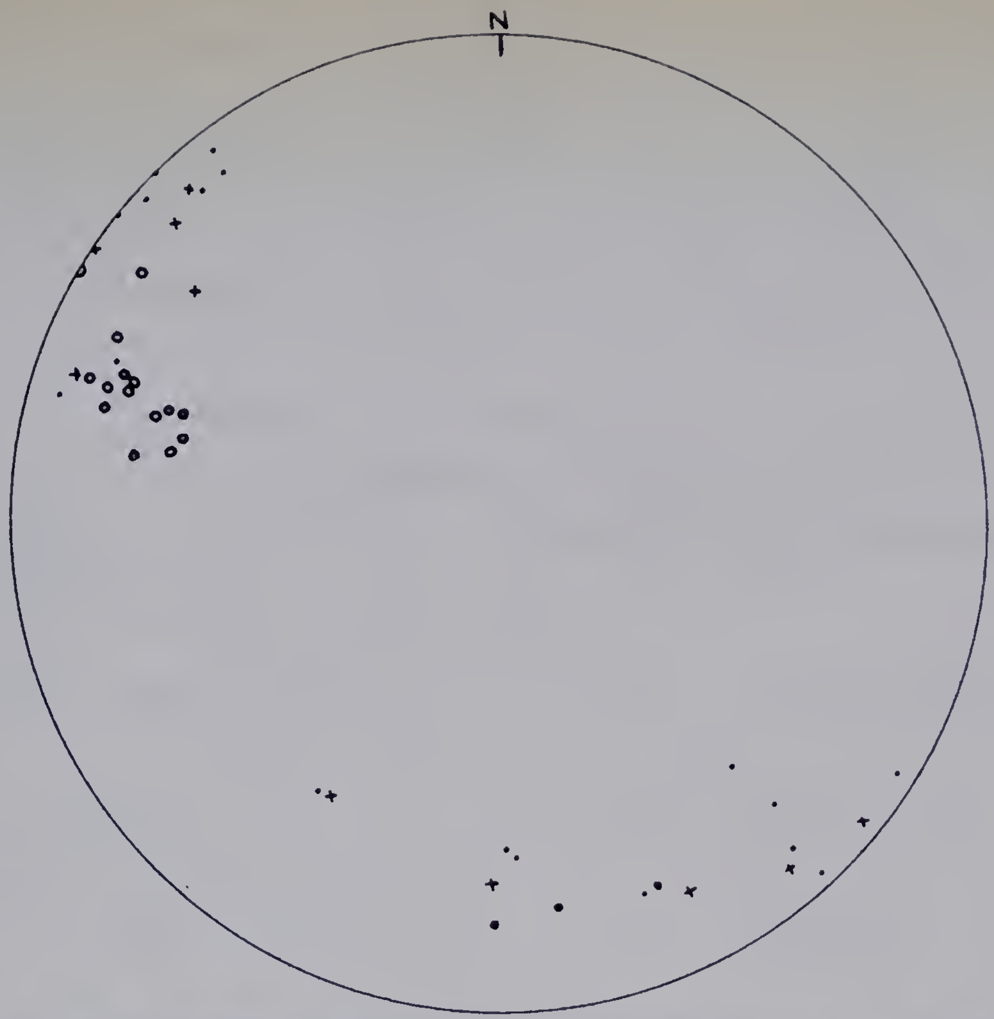


Figure 12 Equal-area diagram showing the orientation of fold axes in the Meadow Creek Anticlinorium determined from pi- and beta-diagrams. Central zone; Subarea I (•), Subarea II (·), Subarea III (×). Southwest limb - folded belt (∘).

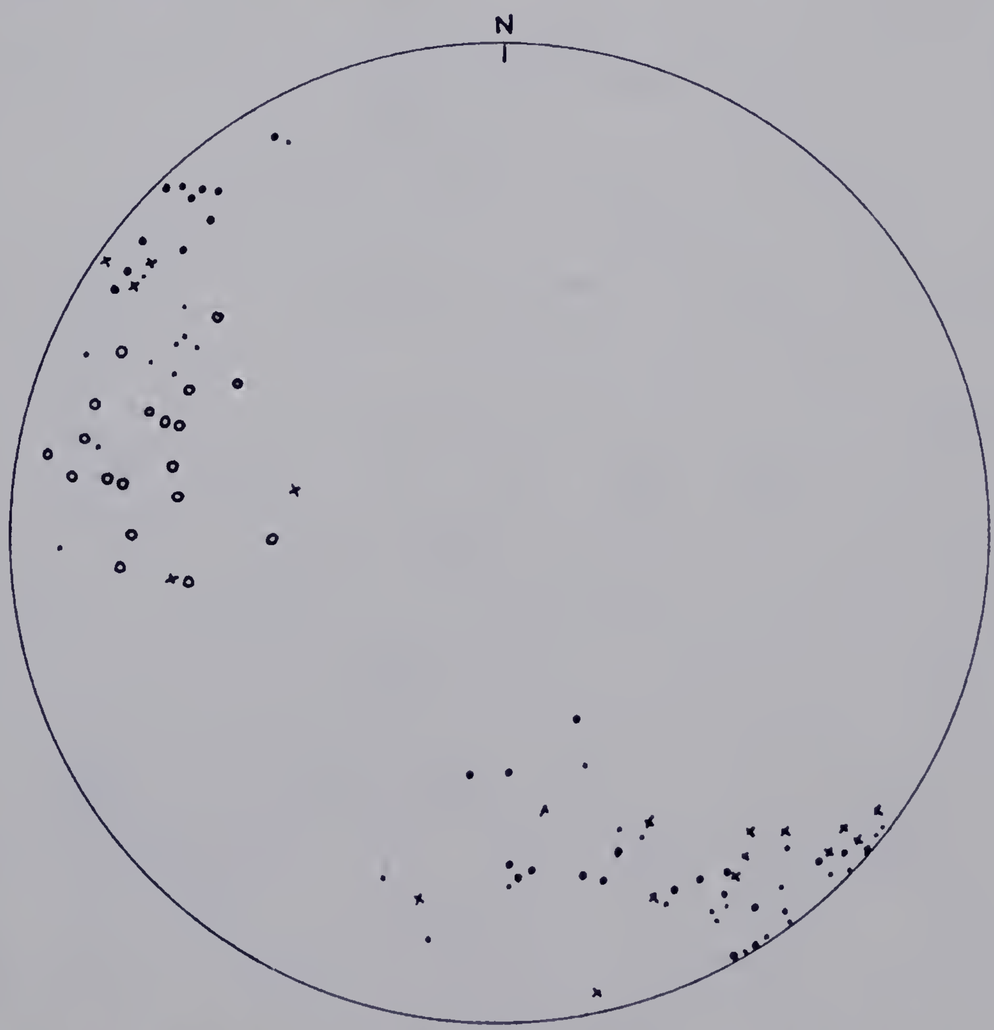


Figure 13 Equal-area diagram showing the orientation of S_1-S_2 intersections (L_{1x2}) in the Meadow Creek Anticlinorium. Central zone; Subarea I (•), Subarea II (·), Subarea III (×). Southwest limb - folded belt (∘).

Figure 14
Rose Diagrams Showing Trend and Direction of Plunge of Fold Axes in the Meadow Creek Anticlinorium

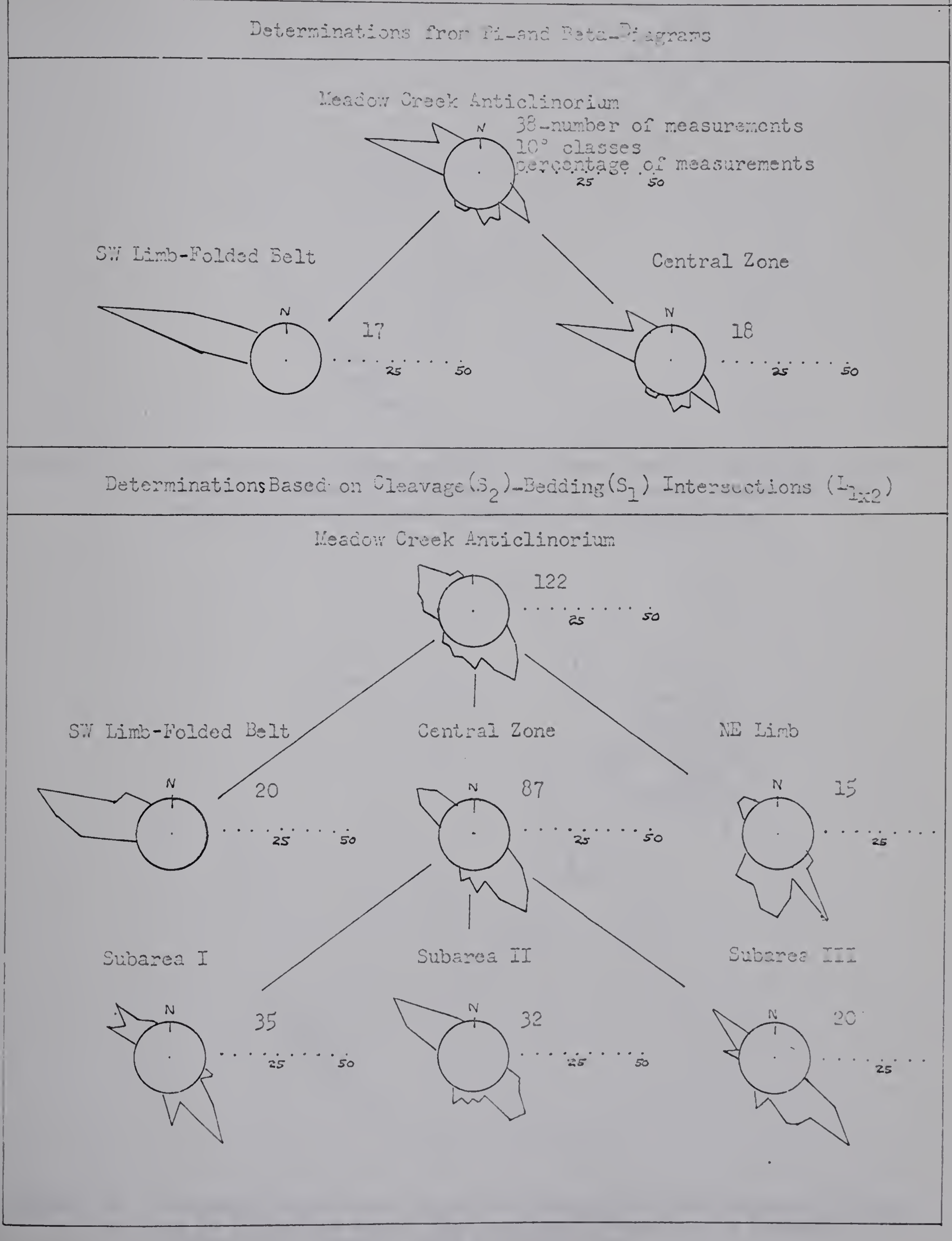


Figure 15 Contoured equal-area projection showing the distribution of poles to 45 S_1 planes in the Wynd and Old Fort Point Formations of Subarea I, central zone, Meadow Creek Anticlinorium.

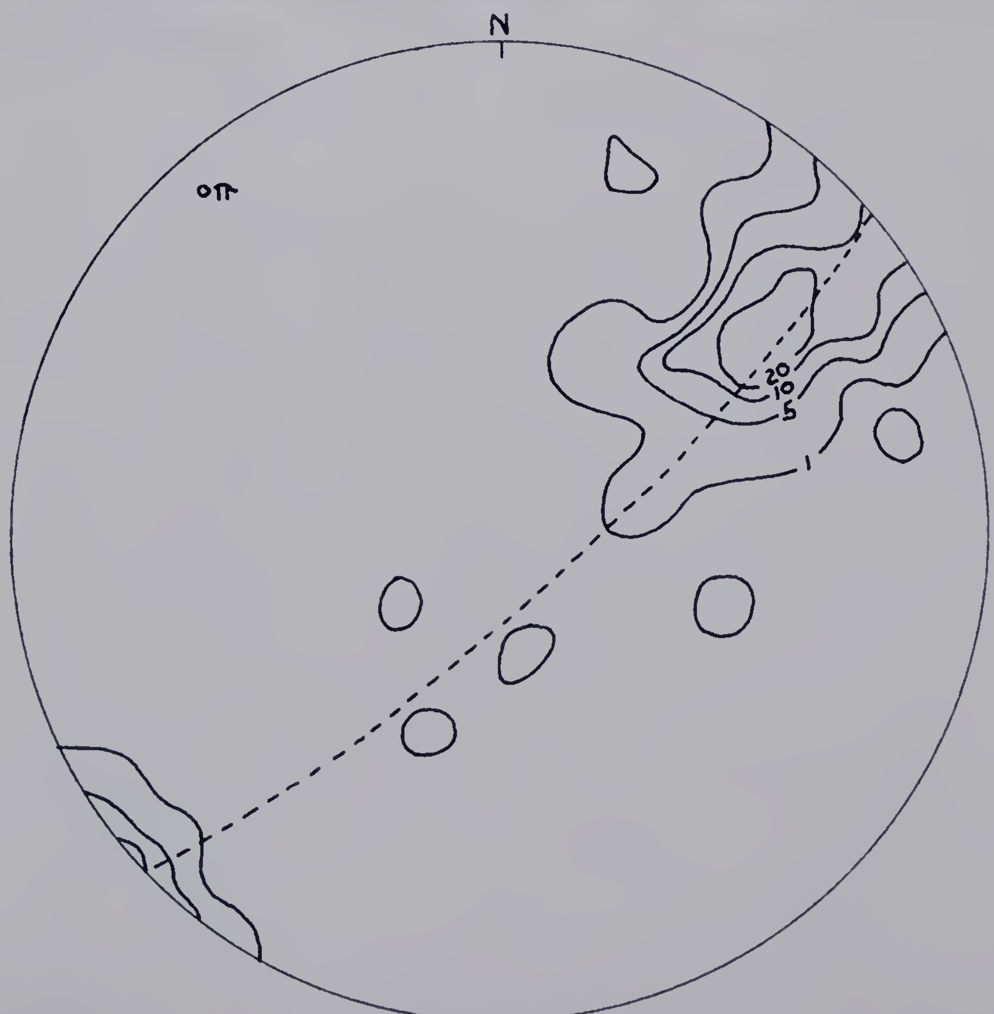


Figure 16 Contoured equal-area projection showing the distribution of poles to 75 S_1 planes in the Old Fort Point Formation of Subarea I, central zone, Meadow Creek Anticlinorium.

Figure 17a	Equal-area diagram showing the orientation of S_1 planes in an overturned anticline in the Old Fort Point Formation, central zone of Meadow Creek Anticlinorium. Normal beds (·), overturned beds (°).
Figure 17b	Equal-area diagram showing the orientation of S_1 planes in an overturned anticline in the Old Fort Point Formation, central zone of Meadow Creek Anticlinorium. Normal Beds (•), overturned beds (°).
Figure 17c	Equal-area diagram showing the orientation of S_1 planes in an overturned syncline in the Wynd Formation, central zone of Meadow Creek Anticlinorium. Normal beds (•), overturned beds (o).
Figure 17 d	Equal-area diagram showing the orientation of S_1 planes in an anticline in the Old Fort Point Formation, Jasper Anticline.

Figure 17a

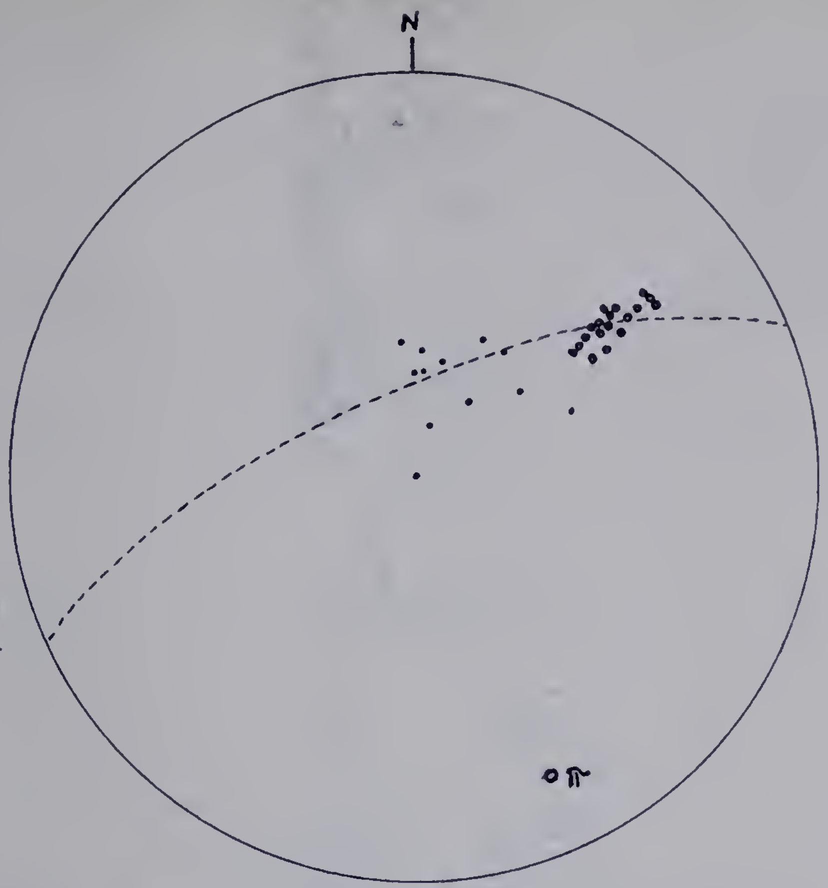


Figure 17b

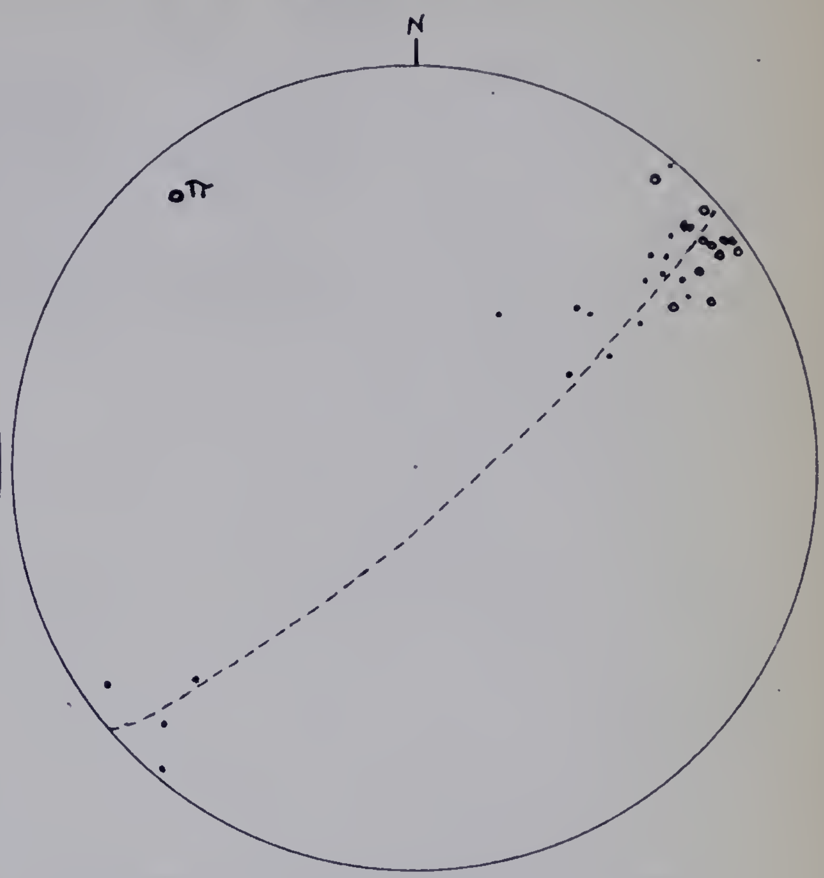


Figure 17c

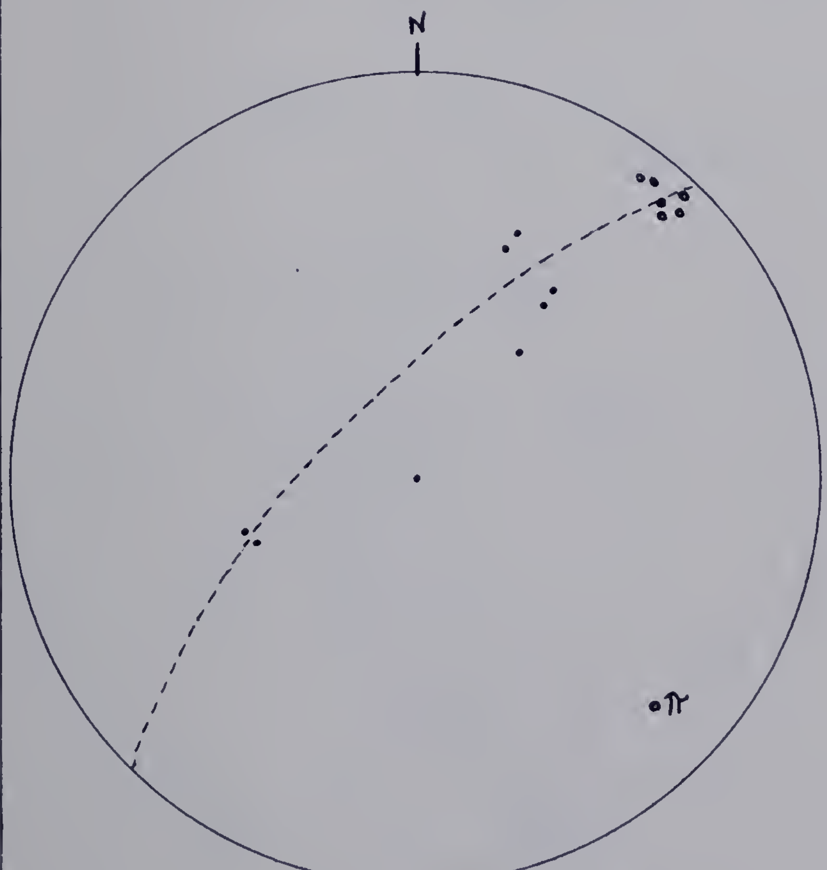
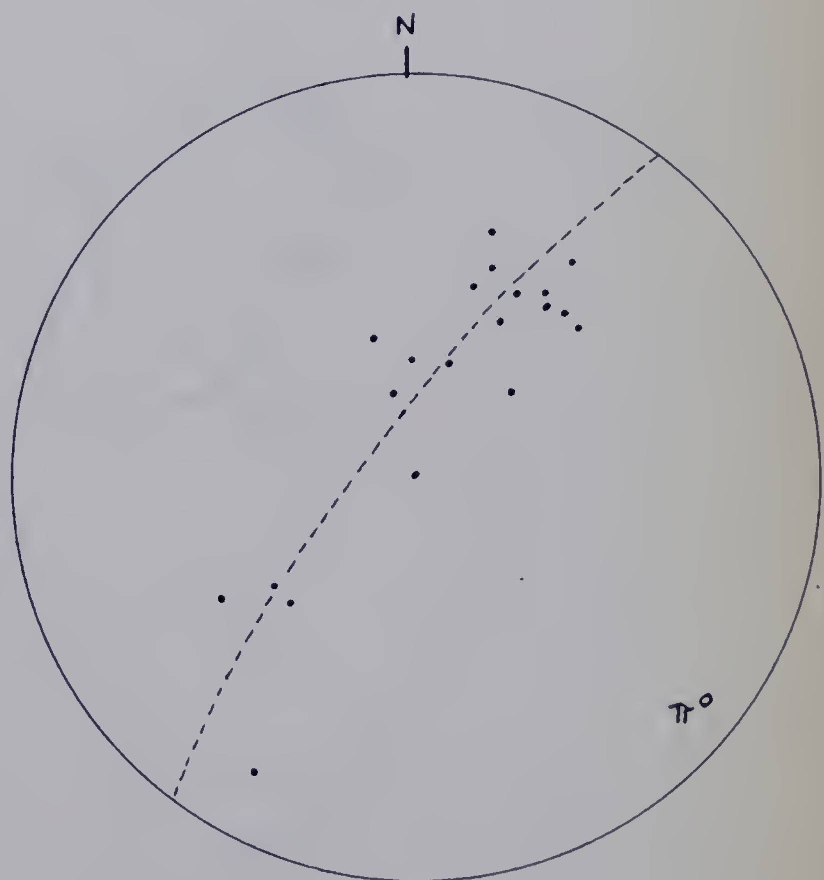


Figure 17d



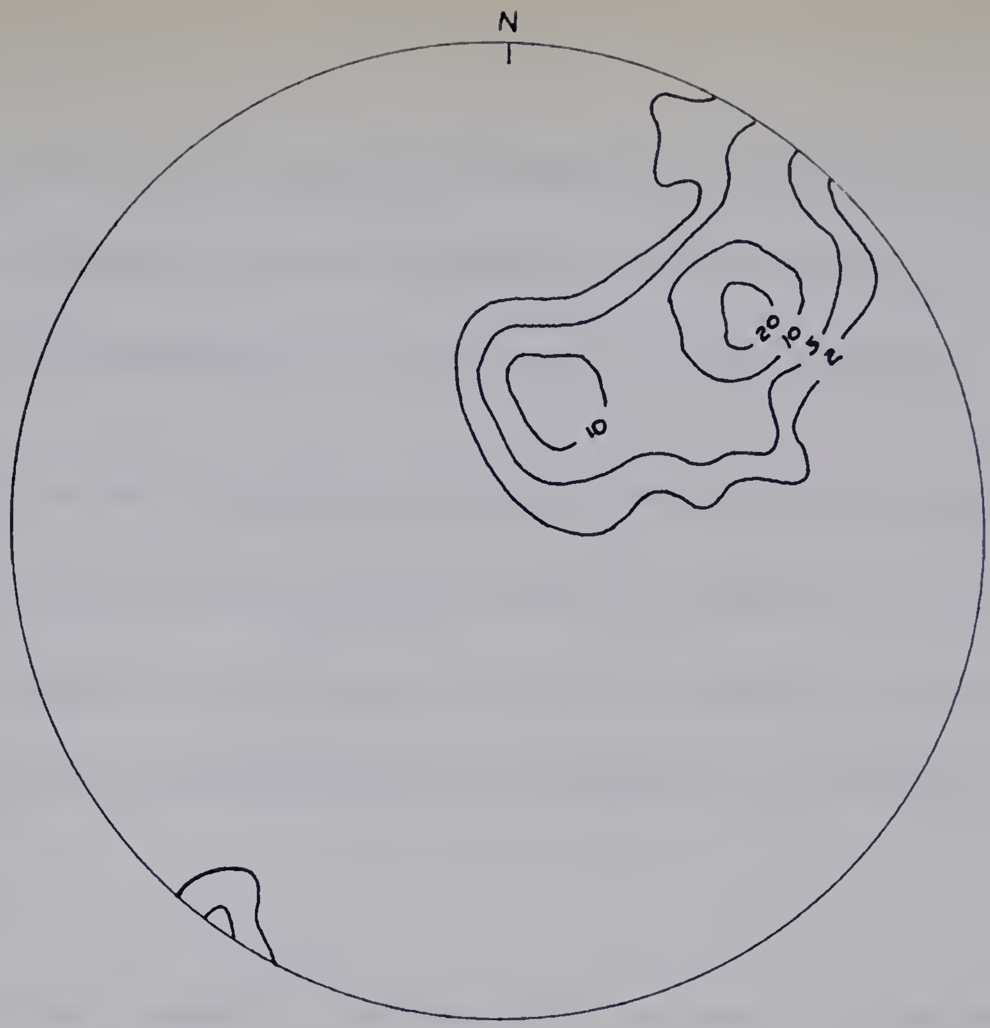


Figure 18 Contoured equal-area projection showing the distribution of poles to 60 S_1 planes in the Old Fort Point Formation of Subarea II, central zone, Meadow Creek Anticlinorium.

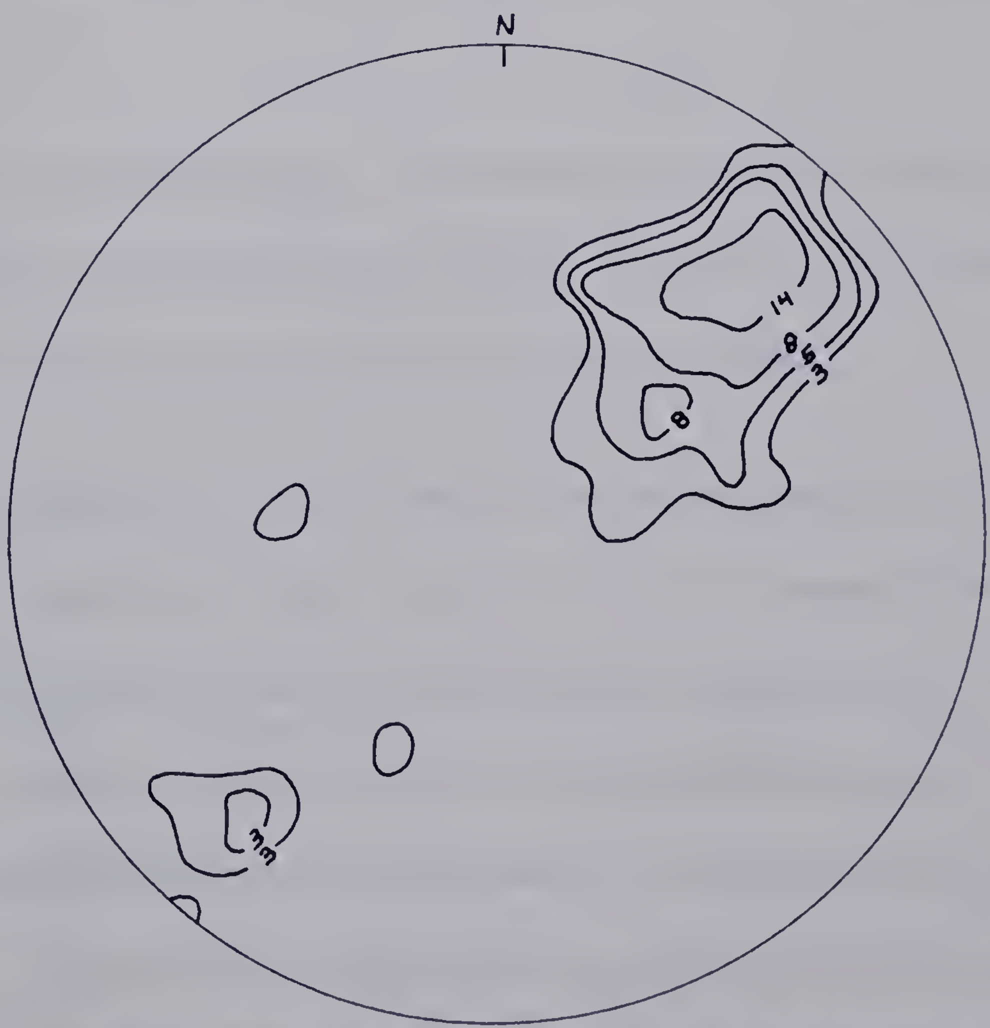


Figure 19 Contoured equal-area projection showing the distribution of poles to 37 S_1 planes in the Old Fort Point Formation of Subarea III, central zone, Meadow Creek Anticlinorium.

folds. In the Jasper Anticlinorium, exposures of folded Old Fort Point strata are more continuous and so a fold was selected for plotting on a pi-diagram (Figure 17d). Again, the scatter of points is considerable and a great circle is not well defined.

No fold can be ideally cylindrical because no fold can be of infinite length in the axial direction. At some point, the fold must become noncylindrical. If a fold is doubly plunging, as appears to be the case in some of the central zone folds, the fold axis in its entirety must be curvilinear and the fold could only be cylindrical over short segments.

In summary then, segments of the folds within the central zone appear to be plane cylindrical (Table 7) but variations in the attitude of fold axes and axial surfaces indicates that nonplane cylindrical and nonplane noncylindrical segments probably are present.

(iv) Orientation Classification - The majority of macroscopic folds in the central zone are of the plunging inclined variety (Table 7). A smaller number of macroscopic and most mesoscopic folds can be classified as horizontal inclined.

(v) Style Classification - Lack of outcrops makes it impossible to construct accurate profiles of macroscopic folds in the Old Fort Point Formation of the central zone. However, the marked thinning of overturned limbs strongly suggests that the folds are of similar rather than concentric style. Mesoscopic folds in Old Fort Point limestones and interbedded slates are well exposed at two locations in the central zone (Plates III-5, IV-1, III-6 and IV-2). The folds in the latter two plates have been analyzed in Figures 20 and 21 using Ramsay's (1962) method. Both the limestones and slates show

TABLE 7: Descriptive Classification of Macroscopic (1) and Mesoscopic (2) Folds in Meadow Creek Anticlinorium

Classification	Region Within Anticlinorium: Central Zone (Wynd and Old Fort Point)	Region Within Anticlinorium: Southwest Limb Folded Belt (Wynd)
Geometry		
In terms of fold axis and axial surface	Plane cylindrical (1) (2) Nonplane cylindrical (1)? Non plane noncylindrical (1)?	Plane cylindrical (1)
Orientation		
Attitude of fold axis and axial surface with respect to external geographic coordinates	Plunging inclined (1) (2) Horizontal inclined (1) (2)	Plunging normal (1) Plunging inclined (1)
Style		
General form of folded surface as seen in profile	Overall pattern likely disharmonic (1) a. Wynd-see SW limb (1) b. OFP-similar (1) (2)	Gross style similar (1) a. Competent concentric b. Incompetent similar
Symmetry		
Defined by fold axis, axial surface and form of folded surface itself	Monoclinic (1) (2) Triclinic (1)?	Orthorhombic (1)

FIGURE 20 PROFILE OF MESOSCOPIC FOLD IN MEMBER B OF THE OLD FORT POINT FORMATION

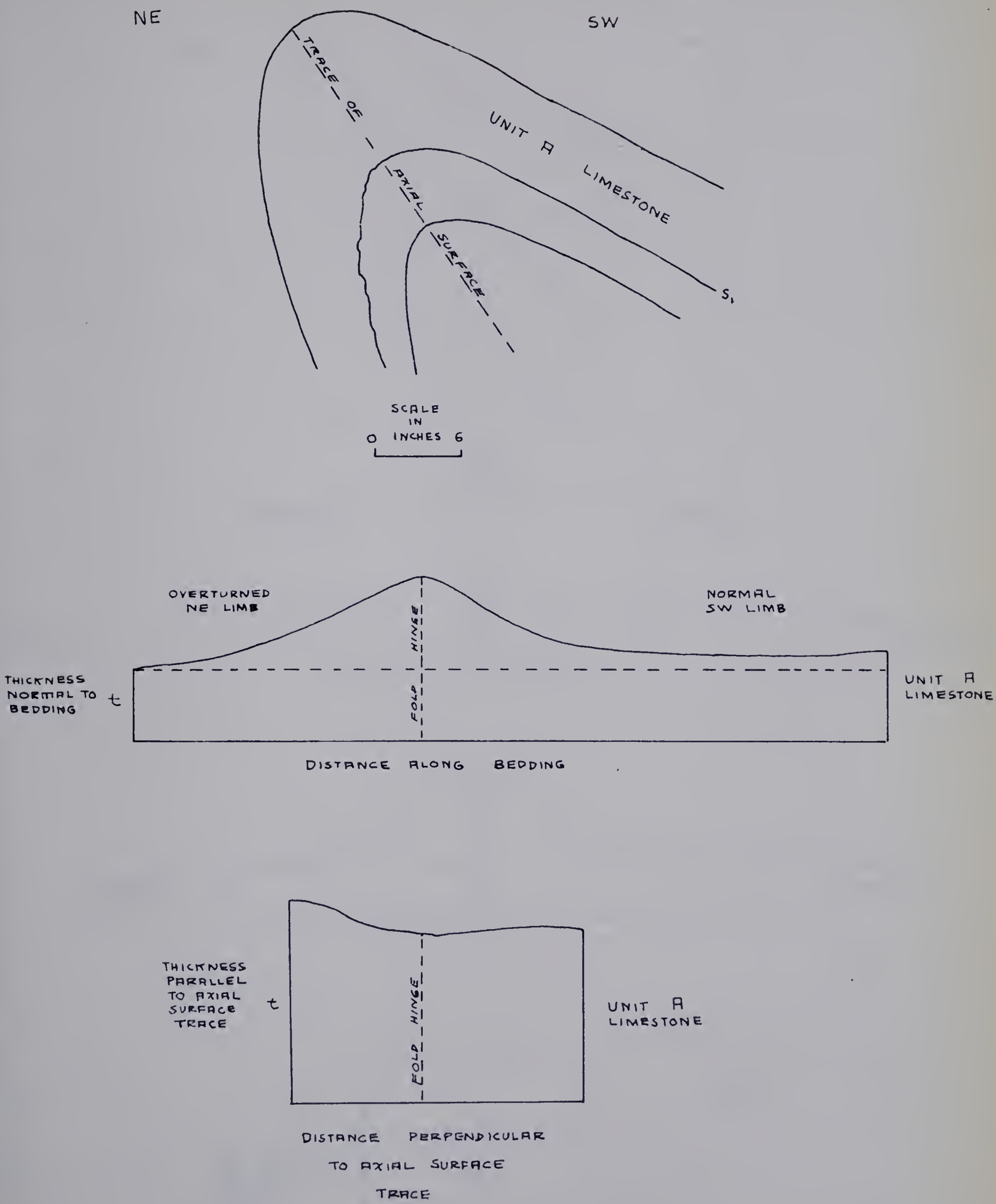
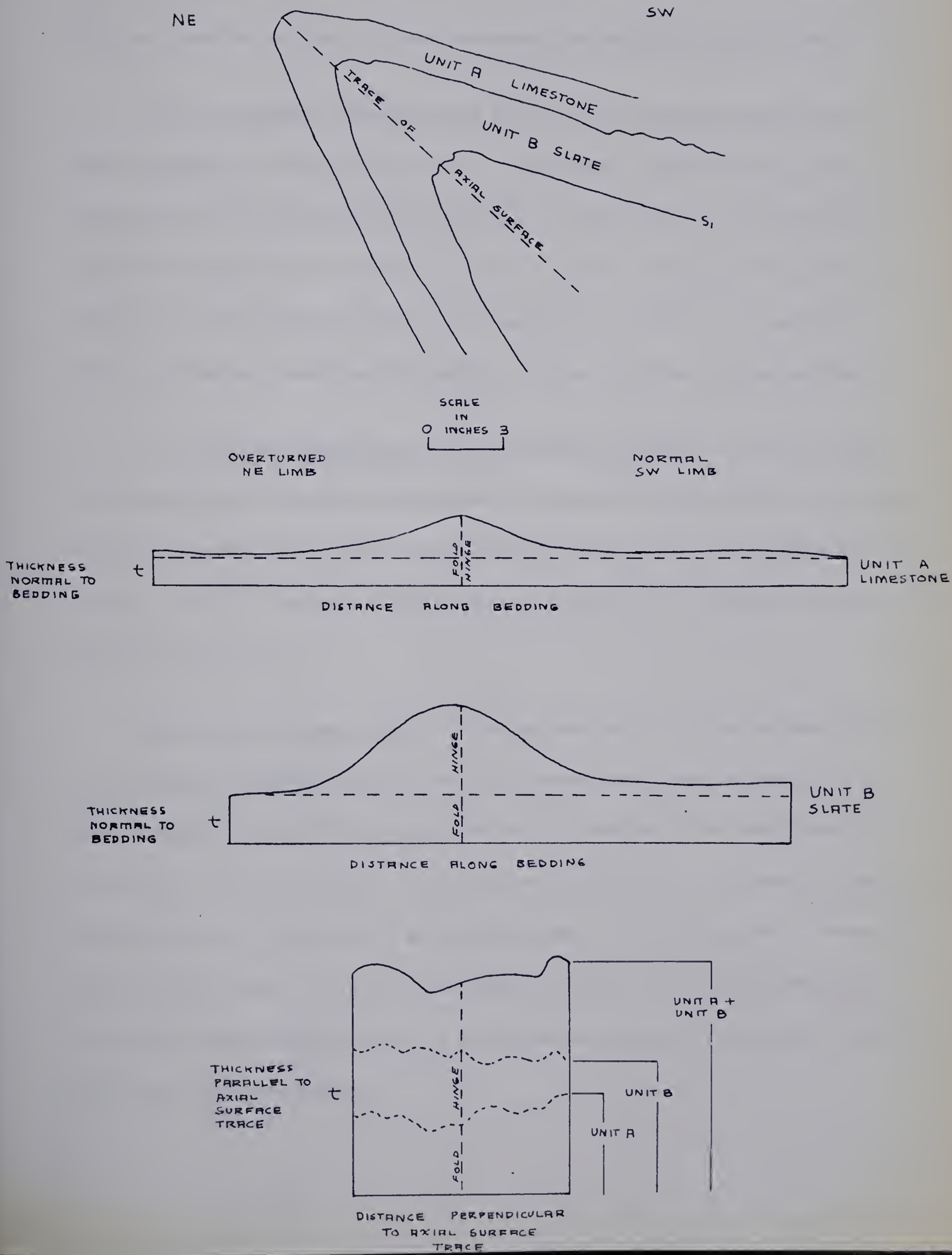


FIGURE 21 PROFILE OF MESOSCOPIC FOLD IN MEMBER B OF THE OLD FORT POINT FORMATION



marked thickening in hinge zones and thinning on overturned northeast limbs. The slates show the greatest variation. Although the thicknesses measured parallel to the axial plane are somewhat variable, the folds are nonetheless decidedly similar in style.

Folds in competent arenaceous beds from the Wynd Formation of the central zone are depicted in Plates III-3 and III-4. Significant changes in thickness of the competent strata in these folds do not appear to have taken place so they can be considered to be approximately concentric in style. In other folds where the proportion of argillaceous beds is greater the folds would tend to be more similar in overall style because of relative thinning and thickening of the less competent argillaceous beds.

(vi) Symmetry Classification - Plane cylindrical segments of overturned folds in the central zone have monoclinic symmetry because the overturned limbs are thinned relative to the other limbs, and the axial surfaces do not bisect the interlimb angles of the folds (Table 7). Segments of folds that are noncylindrical or nonplane cylindrical have triclinic symmetry.

Folds in the Southwest Limb - In the southwestern part of the southwest limb of the Meadow Creek Anticlinorium, the Wynd Formation has been deformed into a series of "open" (Figure 11) plunging anticlines and synclines whose trend is oblique to the folds of the central zone. A comparison of fold profiles in this area with those in the central zone (Figure 22, in pocket) illustrates a number of significant differences between the two areas. In the southwest limb, the folds are more nearly symmetrical, the northeast limbs of anticlines are not overturned nor appreciably attenuated, and the axial surfaces dip more steeply.

(i) Physical Dimensions of Folds - The horizontal distance between adjacent folds in the southwest limb ranges from 100 to 1000 feet and the structural relief varies from 150 to more than 1000 feet (Table 5). Short and long limb lengths range from less than 100 to more than 1200 feet and 100 to more than 1600 feet, respectively.

(ii) Orientation of Component Parts of Folds - Fold axes within the southwest limb trend between 100° and 110° and plunge 15° to 35° NW (Figures 12 and 13). South of the Miette River Valley, the average plunge is about 25°; north of the valley, it is about 35°. The majority of axial surfaces strike N 60° - 75° W and dip steeply (60° to 90°) toward the northeast or southwest. The interlimb angles of the folds are plotted in Figure 11; most of the folds may be classified as "open" compared to the "close" and "tight" folds of the central zone.

(iii) Geometric Classification - The geometry of the folds in the southwest limb is more evident than in the central zone. Figures 23 - 26 are pi-diagrams for this region. The pi-poles and beta-axes (determined by computer) are plotted on each diagram. Figure 23 is a composite diagram which includes all S_1 measurements in the area, whereas in Figures 24 and 25 the area is broken down into domains north and south of the Miette River. In Figure 26, measurements from a single anticline are plotted.

The near linearity of the axial surface traces and the appearance of the folds in profile sections (Figure 27) indicates that the axial surfaces are largely planar. Within this folded belt, the poles to S_1 definitely exhibit a tendency to fall along a single great circle indicating that the folds approach the condition of being cylindrical. Hence the folds may be classified as being plane cylindrical. Fold axis determinations

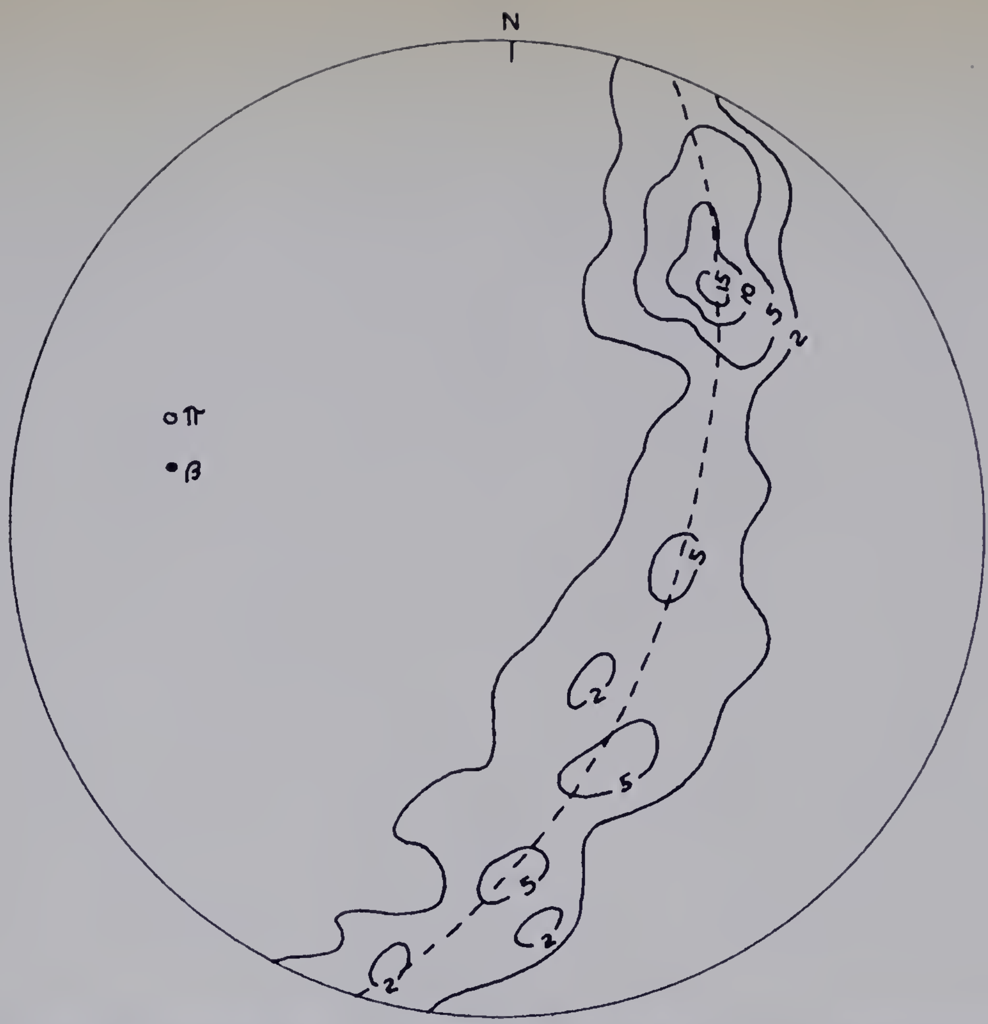


Figure 23 Contoured equal-area projection showing the distribution of poles to 130 S_1 planes in the Wynd Formation of the entire southwest limb - folded belt, Meadow Creek Anticlinorium.

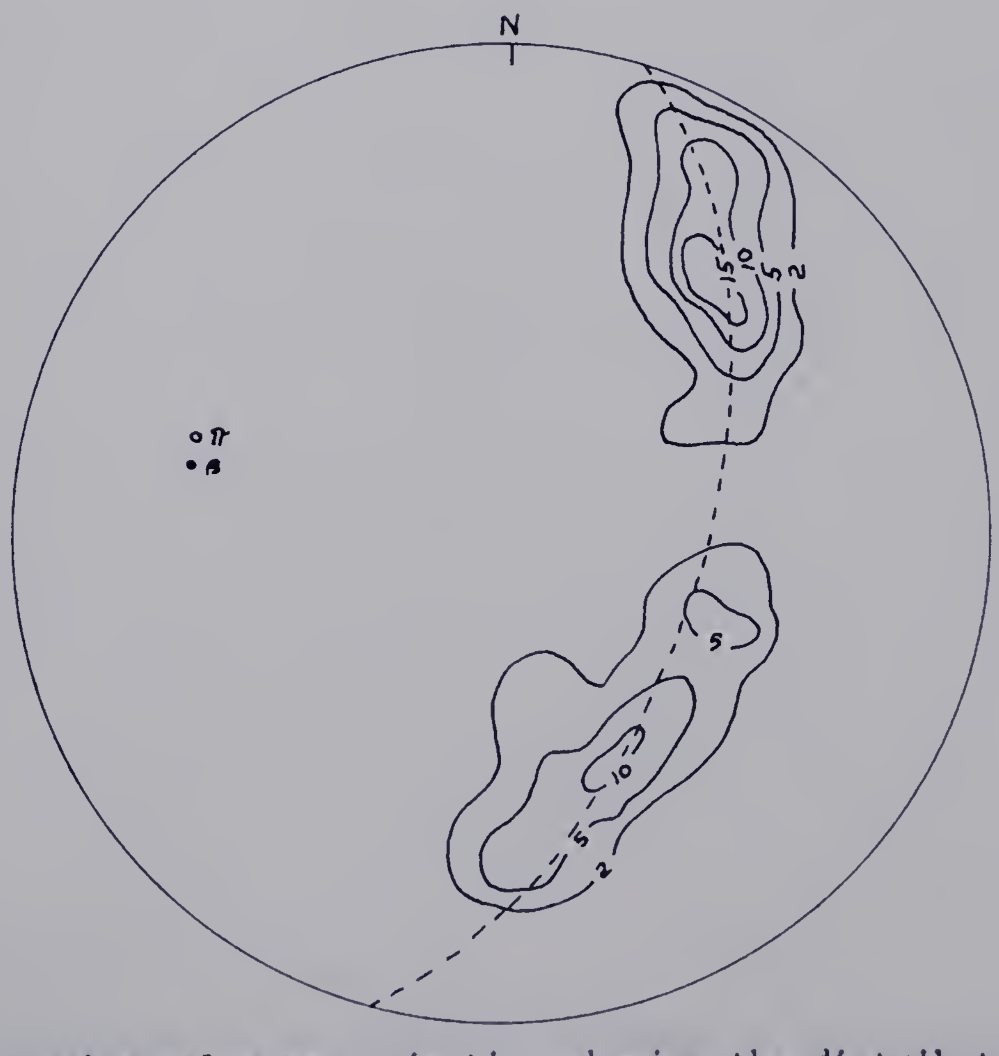


Figure 24 Contoured equal-area projection showing the distribution of poles to 82 S_1 planes in the Wynd Formation of the portion of the southwest limb - folded belt north of the Miette River Valley, Meadow Creek Anticlinorium.

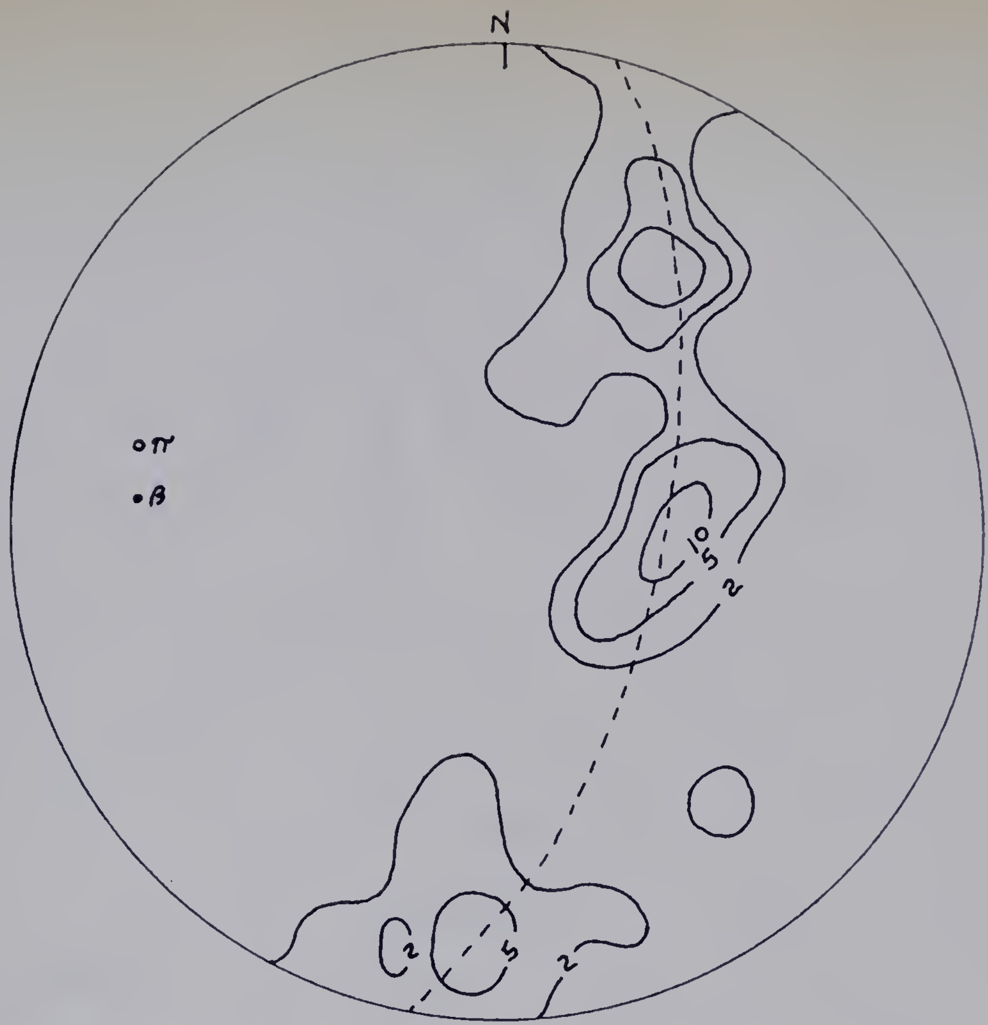


Figure 25 Contoured equal-area projection showing the distribution of poles to 48 S_1 planes in the Wynd Formation of the portion of the southwest limb - folded belt south of the Miette River Valley, Meadow Creek Anticlinorium.

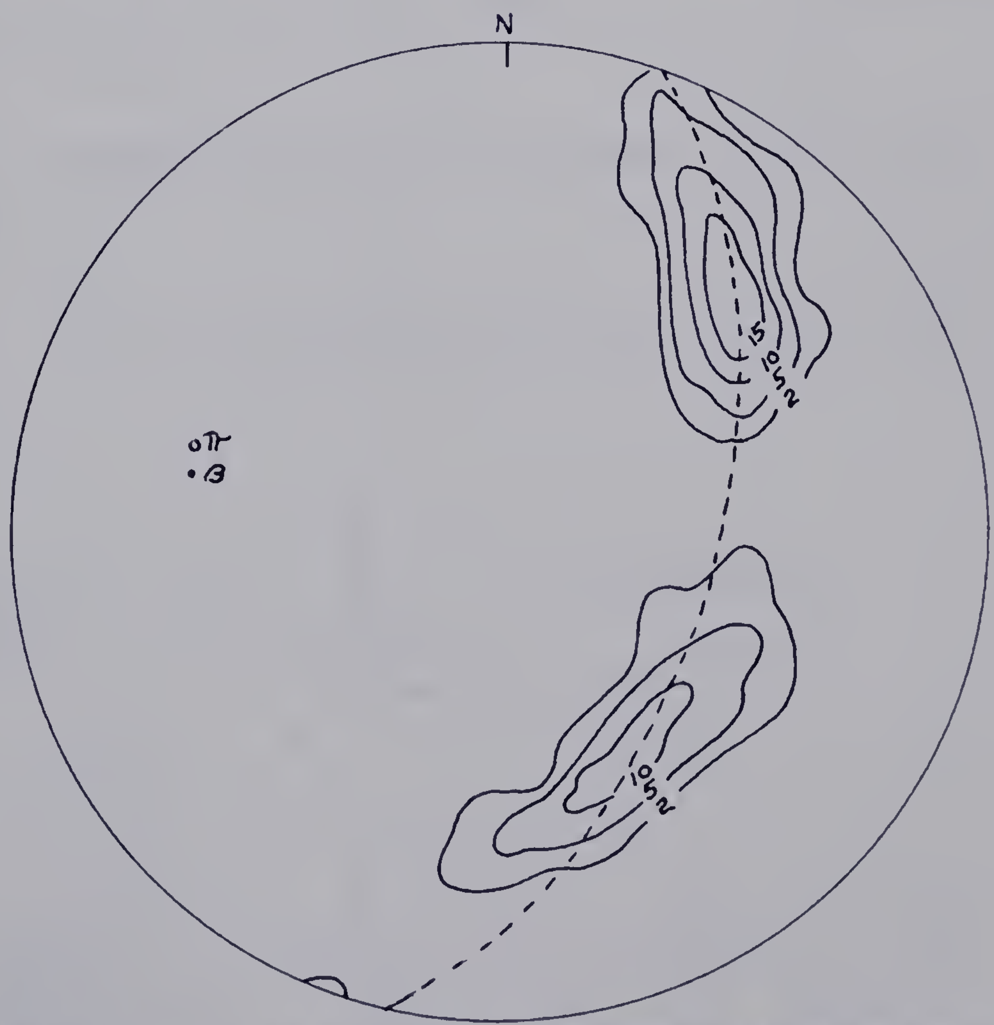
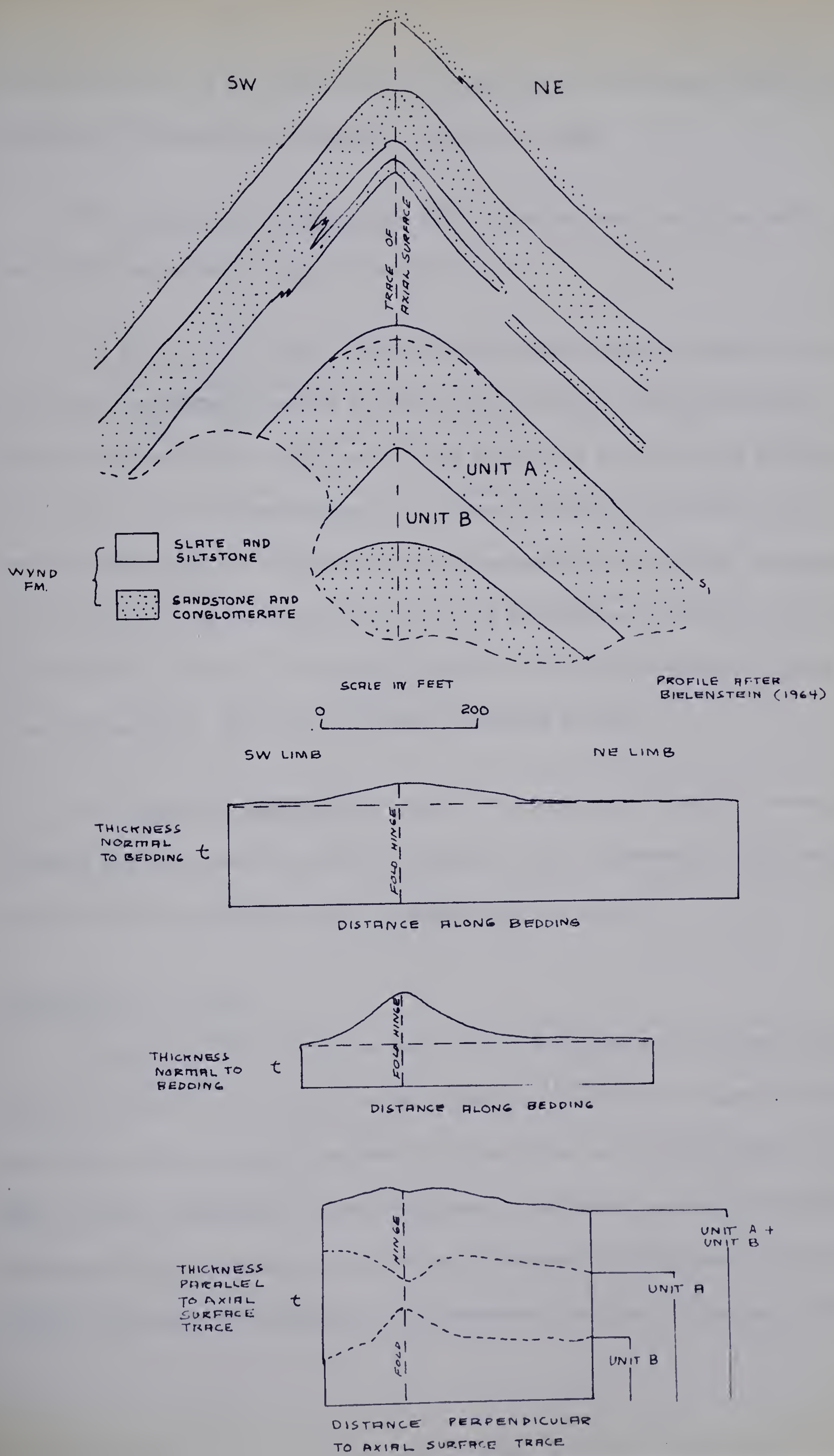


Figure 26 Contoured equal-area projection showing the distribution of poles to 42 S_1 planes in the Wynd Formation in an upright anticline in the southwest limb - folded belt, Meadow Creek Anticlinorium.

FIGURE 27 PROFILE THROUGH IRIS LAKE ANTICLINE



for individual folds in this region (Figures 12 and 13) show a much greater degree of uniformity of attitude than for fold axes in the central zone.

(iv) Orientation Classification - Folds in the southwest limb of the anticlinorium are plunging normal or plunging inclined (Table 7).

(v) Style Classification - Folds in the alternating competent arenaceous and incompetent argillaceous strata of the lower Wynd Formation in the southwest limb (folded belt)probably have profiles very similar to that seen in the Iris Lake Anticline (Figure 27). The competent arenaceous units have tended to fold concentrically, showing only minor variations in thickness measured perpendicular to bedding. Arenaceous Unit A is about 20 percent thicker in the hinge of the fold than in the limbs. The combined thickness of Units A and B measured parallel to the trace of the axial surface is reasonably constant. Thus the overall style of the fold is similar.

(vi) Symmetry Classification - Folds in this region are bilaterally symmetrical in profile and thus possess orthohombic symmetry. This is characteristic of the majority of folds in the lower Wynd Formation throughout the Jasper area.

Interpretation of Folding

Introduction The rocks in the Old Fort Point Formation and lower member of the Wynd Formation were probably buried at depths of 25,000 feet or more when they were folded. Temperatures at the peak of the associated metamorphism probably reached 300° C or more (Chapter 4). Given the regional stress patterns existing during the folding and the environmental controls of confining pressure, temperature and pore solutions, the relative "competency" of "incompetency" of the strata appears to have

been the major factor in determining not only what fold mechanism operated, but also the orientation of the folds produced.

"Competency" in this thesis refers to both the ductility and strength of the rocks at the time they were being folded. "Incompetent" and "competent" strata are rocks with relatively high and low ductility, respectively. The ductility or competency relationship can best be expressed in terms of the mean ductility of the rock sequences and the ductility contrasts within the sequences (Donath and Parker, 1964). The mean ductility of the argillaceous Old Fort Point Formation was greater than that of the overlying predominantly arenaceous Wynd Formation. The ductility contrasts within the homogeneous Old Fort Point Formation were minimal, differences in cohesion between beds were not great, and layering, therefore, was not an important factor in fold development. The marked ductility contrasts between the interbedded arenaceous and argillaceous strata of the lower Wynd Formation resulted in bedding being kinematically active in the formation of the folds.

Kinematic Analysis From the kinematic viewpoint the folds in the Meadow Creek Anticlinorium can be classified as flexural-glide folds and shear (slip) folds.

(i) Flexural-glide Folds - This type of fold developed in the rocks of low mean ductility and high ductility contrast of the lower Wynd Formation. Examples are found in the central zone and southwest limb of the anticlinorium, one is shown in Figure 27.

In flexural-glide folds the bedding is kinematically active. Flexing is accomplished by displacements between and within the layers of argillaceous and arenaceous strata. Displacements are largely parallel to the bedding. The amount of displacement

within the argillaceous units is greater than that in the arenaceous units; this is evidenced by the greater relative thickening of the former units in the hinge zones. This kind of folding can be compared with the bending of a deck of thin cards.

Calculations by Charlesworth (unpublished manuscript) indicate that the strain in the competent and incompetent layers in Figure 27 approximates simple shear. Thinning in the limbs of the fold does not appear to be significant.

The overturned folds in the Wynd Formation of the central zone (Plate III-3 and 4) are also essentially flexural-glide folds. The argillaceous units on the overturned limbs probably underwent some thinning relative to the normal limb. This thinning would occur when the strata were flexed into a steep position that was subparallel to the minimum principal stress axis (σ_3).

In the movement picture of flexural-glide folds, all particles move by relative translation in a plane normal to the fold axis. The kinematic axes may be defined as follows. The glide plane is <u>ab</u> and is parallel to the bedding. The glide direction is <u>a</u> and it is normal to the fold axis B. The <u>b</u> kinematic axis is normal to <u>a</u> and is an axis of bending. The <u>c</u> axis is normal to the <u>ab</u> glide plane. The attitude of <u>a</u> and <u>c</u> will change throughout the fold as the dip of the beds changes.

(ii) <u>Shear</u> (<u>Slip</u>) <u>Folds</u> - Shear folds developed in the more ductile (less competent) argillaceous strata of the Old Fort Point Formation in the central zone of the Meadow Creek Anticlinorium. These folds are typically similar in style, asymmetrical, and have overturned and attenuated northeast limbs.

The shear folds probably developed initially as flexural folds, extensions of the folds in the overlying Wynd Formation. Sometime after the folds had started to develop, another mechanism - slip along closely spaced parallel shear surfaces oblique to bedding- became the principal means of fold formation. Slip along these shear surfaces (displacement discontinuities) caused translation and rotation of the bedding. Flexuring may have continued but was of decreased importance. Because the slip was in most cases not restricted by bedding layer boundaries, bedding was kinematically passive and exerted little or no influence on the development of the folds. Bedding merely serves as an indicator of the overall deformation.

The surfaces along which the slip occurred are assumed to be planes of weakness created by the development of slaty cleavage (S_2) in the rocks. The formation of shear folds is thus closely linked with the phenomenon of cleavage development. Although the slaty cleavage is believed to have formed normal to σ_1, the maximum principal stress (de Sitter, 1959), displacements would have occurred along S_2 planes whenever they had been rotated into a position not normal to σ_1. Displacements along slaty cleavage can be seen in Plate VIII-2. Slickensided cleavage surfaced have been observed in the field. The slickensides are roughly normal to the fold axes.

Another important facet of the fold development was the strain of the material between the slip surfaces. This strain consists of a contraction parallel to σ_1, and an extension normal to σ_1, roughly parallel to the cleavage. Such an elongation and contraction is evident in the folding and crumpling of the slate between the cleavage planes in Plate VI-5.

Progressive shortening within the Old Fort Point took place by "flattening" (Ramsay, 1962) of the folds. Variations in the amount of flattening accounts for the variation in the direction and angle of plunge of the fold axes within the central zone. Ramsay (*ibid.*) has shown how flattening of the flexural fold will result in a similar fold. Using Ramsay's method of quantitative estimate has been made of the amount of flattening in the anticline in Figure 20. This fold in limestone probably began as a flexural fold. The average value of flattening obtained is 45 percent.

Attenuation of the overturned limbs of the shear folds probably occurred when these limbs were rotated into a position subparallel to σ_3. Measurements by this writer of the thickness of a large number of limestone beds (Figure 28) suggests that the median thickness of the beds decreases as the amount of overturning increases. Beds on the southwest limbs of folds do not appear to have been thinned. They would have been more oblique to σ_3.

The movement picture in a developing shear (slip) fold may be considered as follows. All movement of particles is parallel to the slip (S_2) planes. The glide plane is *ab*. The glide direction is the *a* kinematic axis and *b* is normal to *a* but not necessarily parallel to the fold axis B. The normal to the *ab* plane is *c*; its attitude is reasonably constant throughout a shear fold. This is in contrast to the variable attitude of *c* in flexural-glide folds.

Dynamic Analysis Most of the folds in the arenaceous lower Wynd Formation have steeply dipping to vertical axial surfaces. Folds in the underlying argillaceous Old Fort Point Formation have moderately to gently inclined southwest dipping axial surfaces (Figures 11 and 22). This difference in attitude can be accounted for by

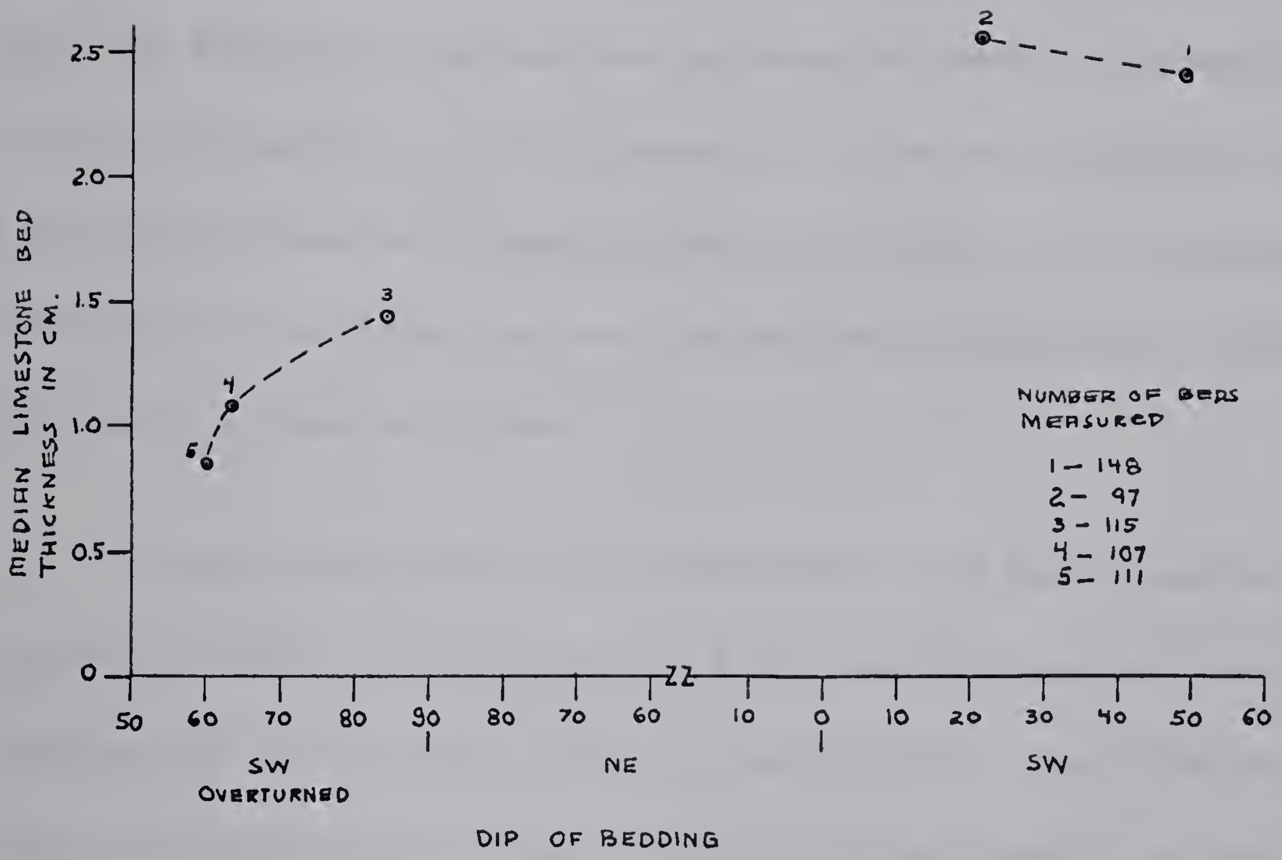


FIGURE 28 THICKNESS OF LIMESTONE BEDS PLOTTED AGAINST DIP OF BEDDING IN FOLDS IN OLD FORT POINT FORMATION, CENTRAL ZONE, MEADOW CREEK ANTICLINORIUM.

the difference in competency of the two lithologic sequences.

Charlesworth (1959) has suggested that during the thrusting and folding of the Rocky Mountains, the maximum principal stress trajectories probably plunged northeast. The intermediate principal stress trajectories paralleled the northwest-southeast trending ranges and the minimum principal stress trajectories plunged southwest. If the Wynd and Old Fort Point Formations are considered as a competent sheet overlying an incompetent sheet, then the regional maximum principal stress trajectories would tend to be refracted towards the horizontal in the Wynd Formation. This refraction would give rise to folds in the Wynd with vertical to steeply dipping axial surfaces. In the incompetent Old Fort Point, the stress trajectories would not tend to be refracted and folds with southwest dipping axial surfaces would form.

The overturned folds in the Wynd Formation of the central zone are probably a transitional feature, their geometry being influenced by the close proximity of the underlying Old Fort Point folds. The more westerly trend of the folded belt of Wynd strata in the southwest limb of the anticlinorium may be related to counter-clockwise rotation along the underlying Pyramid thrust, or it may have been caused by an unrecognized thrust fault.

Cleavage

Introduction

Rock cleavage is a common and important feature of the deformed Proterozoic strata of the Jasper area. Three different types of cleavage, believed to have formed contemporaneously, can be recognized. In view of the controversy surrounding the origin of cleavage (see e.g. Gonzalez Bonorino, 1958) it seems wise to avoid, where possible, names which gave genetic implications. The three types of cleavage, in their order of importance, are:

(1) Slaty Cleavage - Cleavage dependent upon the parallel or subparallel arrangement of the majority of platy mineral constituents (phyllosilicates) in a rock. Other terms commonly used to denote this kind of cleavage include "schistosity" (White, 1949, p. 587) and "flow cleavage" (Leith, 1905, p. 23). It is also referred to in this thesis as S_2.

(2) Fracture Cleavage - The tendency to split along closely spaced parallel or subparallel surfaces of fracture or near fracture. The surfaces, although they may be associated with some degree of parallel arrangement of platy minerals, are not directly controlled by such an arrangement.

(3) Slip or Strain-slip Cleavage - A variety of cleavage, in which visible displacements have occurred along discreet cleavage surfaces is commonly crumpled or folded.

Cleavage planes are planar discontinuities, imposed fabric elements which originated during an episode of rock deformation. Slaty cleavage, as a consequence of its almost universal occurrence in argillaceous strata of the Old Fort Point and

lower Wynd Formations, may be regarded as a penetrative discontinuity (Turner and Weiss, 1963, p. 28) on most scales of observation (Plate IV-4). Fracture and slip cleavage are less commonly developed and are therefore not penetrative to the degree that slaty cleavage is.

In the Jasper area, which has apparently undergone only one major episode of folding and cleavage development, slaty cleavage can be utilized as a "tool" to help determine: (l) the approximate orientation of axial surfaces of folds, (2) the "way-up" of the beds, and (3) the directions in which anticlines and synclines are located with respect to an outcrop.

Slaty Cleavage

Occurrence Slaty cleavage (S_2), as the name implies, is most prominently developed in the slates of the Old Fort Point and lower Wynd Formations. In most slate outcrops, it is the dominant fabric element; bedding (S_1), although generally recognizable, is usually much less prominent (Plate IV-3).

Hand Specimen Description Very fine-grained slates can be split along S_2 into thin smooth sheets less than 1 mm thick. As silt and carbonate content increases,

the distance between planes of parting also increases and the surfaces become rougher. The cleavage planes serve as pathways for solutions and hence are commonly discolored with iron oxide weathering films.

Thin Section Description The parallel to sub-parallel arrangement of muscovite and chlorite flakes is quite apparent in thin sections of slate. The longest dimension of the flakes rarely exceeds 0.04 mm. In places, the chlorite and muscovite are concentrated in narrow parallel zones consisting of platy minerals only (Plate VIII-1). These zones or domains are separated by zones of 0.02 mm or more in thickness in which are located silt-sized angular grains of quartz and feldspar. The longest dimension of the silt-sized grains is often conspicuously oriented parallel to the cleavage. Chlorite and muscovite flakes adjacent to the silt grains are bent around them.

Scattered throughout most Old Fort Point slates are books consisting either of chlorite, muscovite or a combination of the two minerals. Maximum length of the books is about 0.4 mm. In slates that display well-developed cleavage, the books are ellipsoidal in shape and their long axis is parallel to cleavage. The "c" crystallographic axis tends to parallel the long axis of the books and thus parallel slaty cleavage. In poorly cleaved rocks, the ellipsoidal or tabular shaped books are parallel to bedding (S_1) and the "c" axes are at right angles to the long dimension of the books (Plate VIII-3). Some of the books display well-developed "kink" bands (Plate VIII-3), and wavy extinction is almost universal. Their origin is discussed below.

Obliteration and Transposition of Bedding As mentioned previously, bedding (S_1) can almost always be located in an outcrop of slate though one may have to spend some time searching for color changes or thin silty markers not obscured by the cleavage.

In thin section, S_1 is best recognized by the presence of occasional silty laminae of quartz and feldspar grains. In the dominantly argillaceous portions between these laminae, it is often impossible to recognize S_1. Transposition of bedding (Turner and Weiss, 1963, p. 92-94) has occurred only rarely where individual laminae have been severely disrupted by displacements along cleavage planes (Plate VIII-2).

Secondary Mineralization Along Cleavage Cleavage planes have rarely served as loci for crystallization of secondary minerals. In one outcrop, where tightly folded limestones and calcareous slates are adjacent to a normal fault, the cleavage was "opened up" during the development of the faults and calcite crystallized along the planes of parting (Plate VI-3).

Orientation of Slaty Cleavage Throughout the Meadow Creek Anticlinorium there are significant variations in the attitude of slaty cleavage. The orientations of mean S_2 planes are listed in Table 8. The location and attitude of individual S_2 measurements are plotted in Figure 10. Poles to S_2 throughout the whole map-area are shown in Figure 29.

The strike of slaty cleavage is consistent throughout the whole of the central zone and approximates the strike of the axial surfaces of the folds (Figure 31). Mean values of strike range from N 41° W to N 50° W. All slaty cleavage planes dip toward the southwest but the value of dip varies from subarea to subarea (Table 8). The mean dip of cleavage, both northeast and southwest limbs considered decreases progressively from the northwest to the southeast along the trend of the central zone. In Subarea I, it is 61° SW; in Subarea III, it is 42° SW (Figures 30, 32 and 33). This decrease in dip accompanies a similar decrease in the dip of the axial surfaces of the folds.

TABLE 8: Mean Slaty Cleavage Planes in the Meadow Creek Anticlinorium

Zone	Area		Attitude of Mean Cleavage Planes: Strike	Dip	95% Confidence Radius in degrees	Number of Readings
Central Zone	Whole Area	in NE limbs	N 43° W	52°SW	2.7	102
		SW limbs	N 47° W	60°SW	10.0	20
	Subarea I	Both limbs	N 41° W	61°SW	4.0	58
		NE limbs	N 41° W	58°SW	3.5	51
		SW limbs	N 46° W	81°SW	16.0	8
	Subarea II	Both limbs	N 44° W	52°SW	5.7	36
		NE limbs	N 42° W	52°SW	4.4	25
		SW limbs	N 47° W	47°SW	7.9	10
	Subarea III	Both limbs	N 49° W	42°SW	4.6	29
		NE limbs	N 50° W	42°SW	5.0	27
		SW limbs	N 47° W	44°SW	20.6	2
SW Limb-Folded Belt	Whole Area	NE limbs	N 75° W	78°SW	8.5	13
		SW limbs	N 60° W	67°SW	12.9	13
	North of Miette River	NE limbs	N 80° W	81°SW	11.4	8
		SW limbs	N 76° W	79°SW	16.9	4
	South of Miette River	NE limbs	N 77° W	73°SW	13.0	5
		SW limbs	N 57° W	62°SW	15.0	9

*In overturned folds of central zone, both limbs dip SW. "NE limbs" refers to overturned limbs of anticlines and synclines and "SW limbs" refers to normal dipping limbs.

Figure 29 Contoured equal-area projection showing the distribution of poles to 152 S_2 planes in the Meadow Creek Anticlinorium.

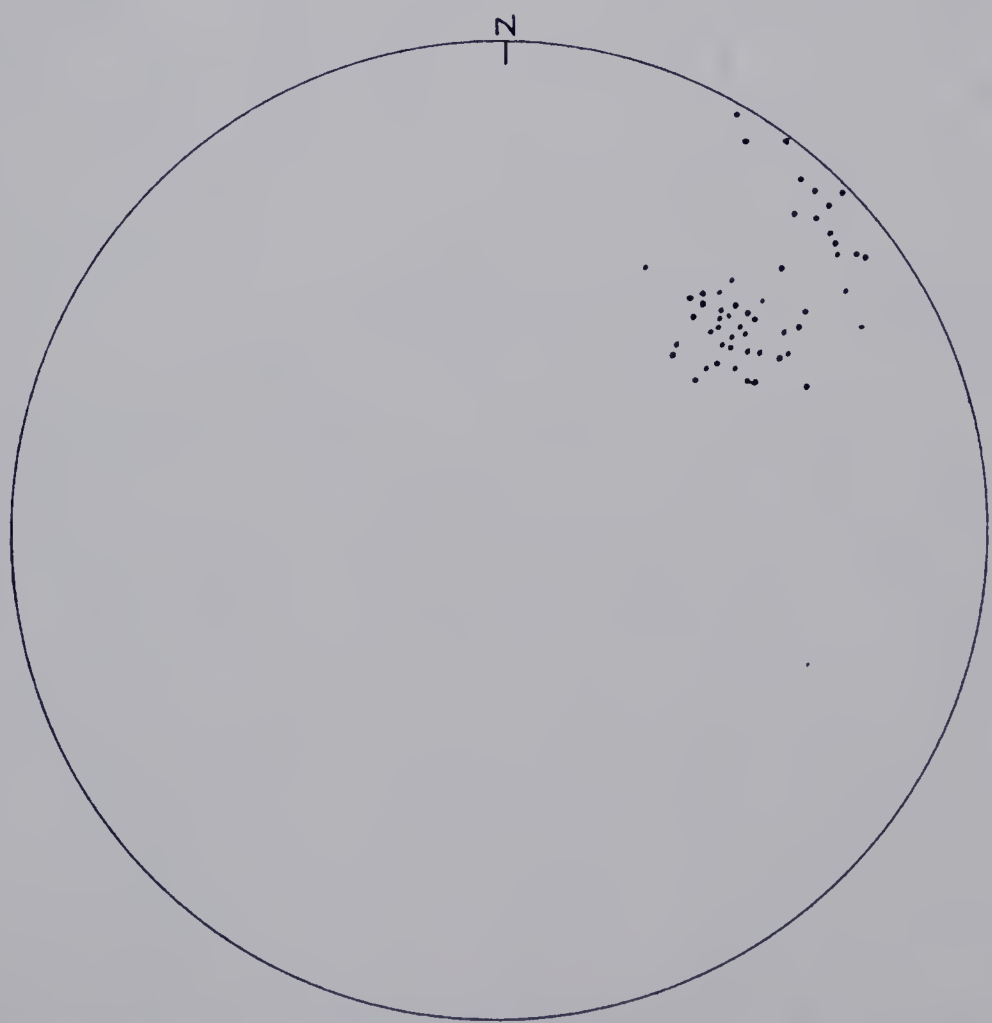
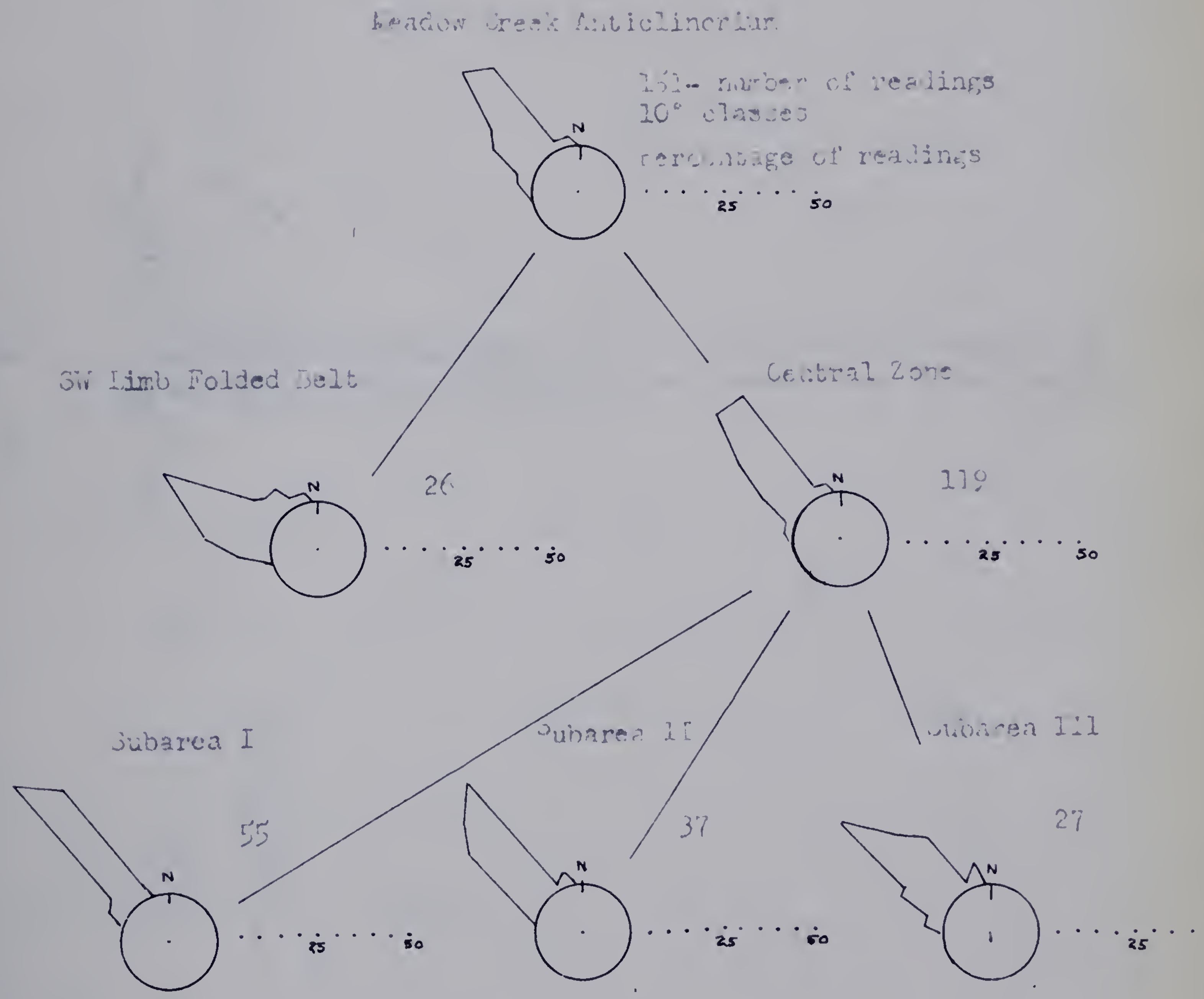


Figure 30 Equal-area diagram showing the orientation of 56 poles to S_2 planes in the Subarea I of the central zone, Meadow Creek Anticlinorium.

Figure 31

Rose Diagrams Showing Strike of Slaty Cleavage in the Meadow Creek Anticlinorium



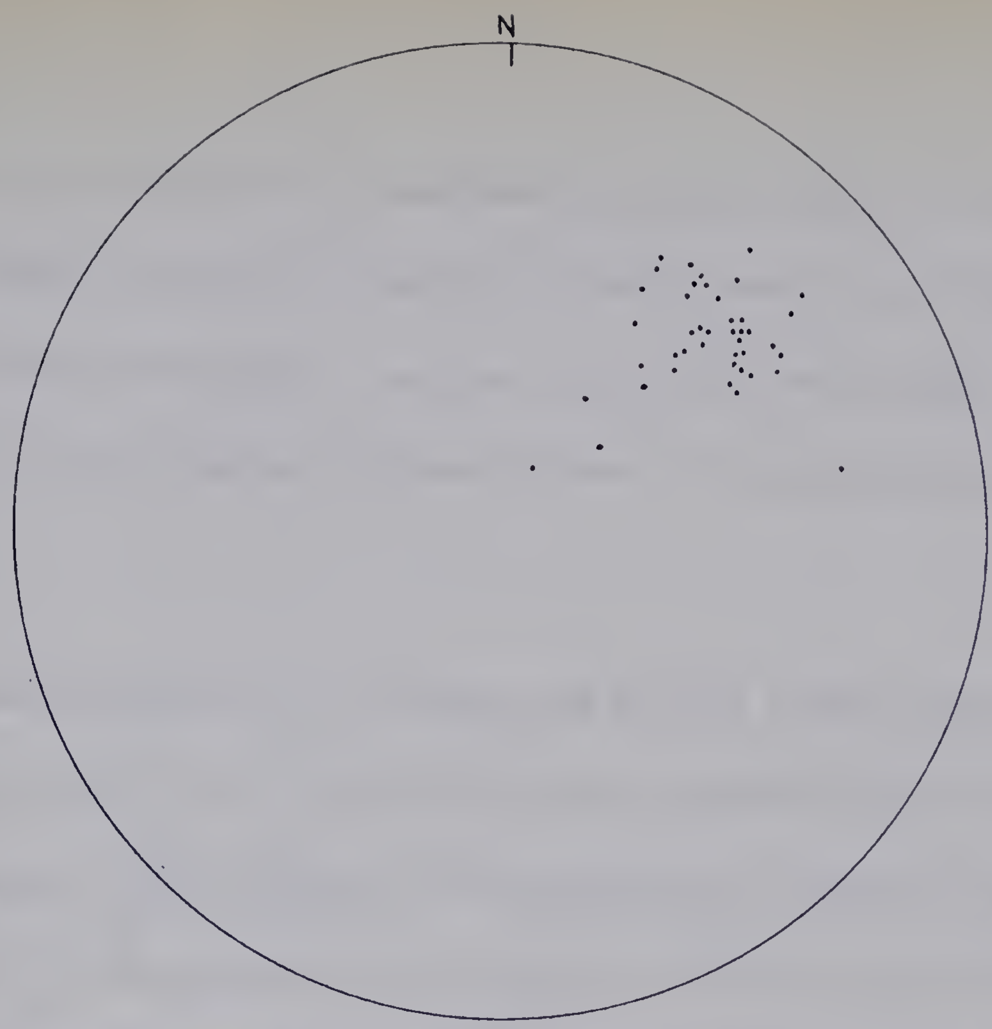


Figure 32 Equal-area diagram showing the orientation of 44 poles to S_2 planes in Subarea I, central zone, Meadow Creek Anticlinorium.

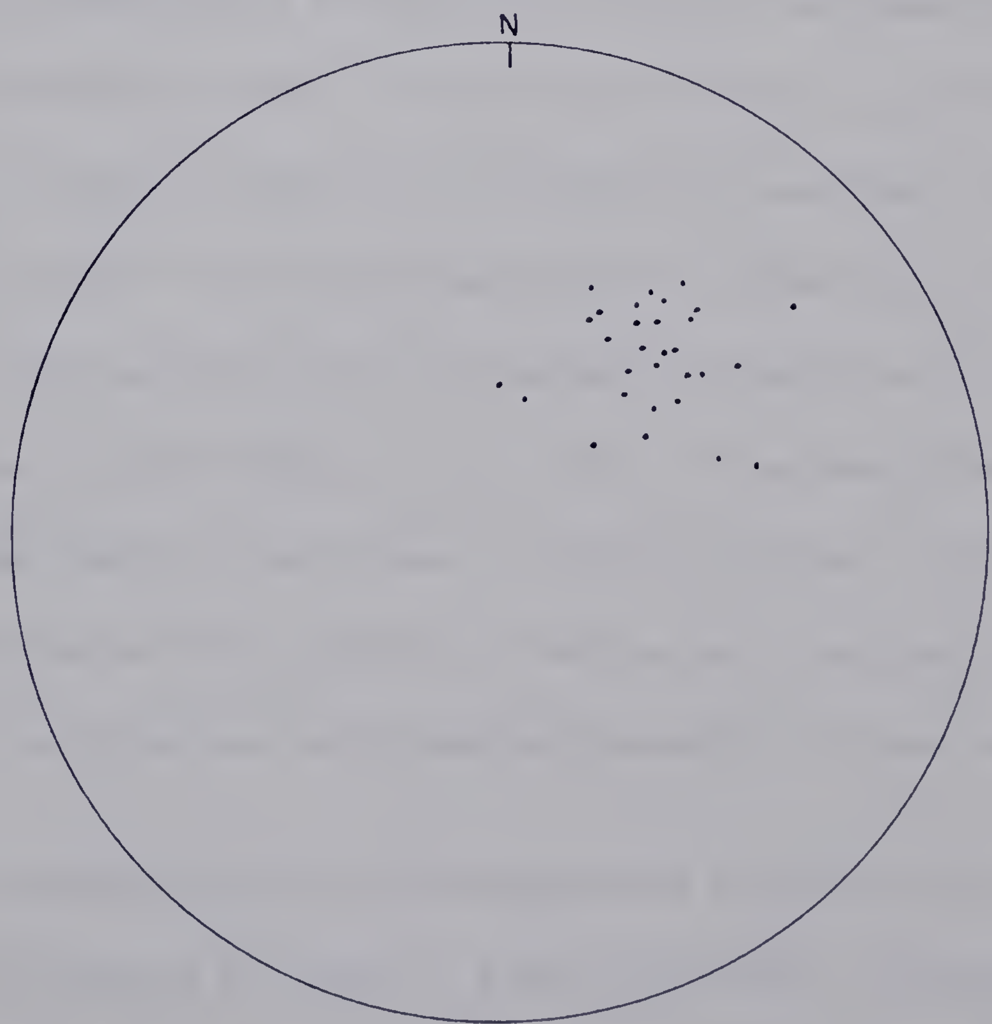


Figure 33 Equal-area diagram showing the orientation of 30 poles to S_2 planes in Subarea III, central zone, Meadow Creek Anticlinorium.

The rather limited number of S_2 measurements from southwest (normal) dipping limbs (Figure 35) makes it impossible to determine whether there is any difference in dip of S_2 from northeast (overturned) to southwest limbs in the central zone. Other evidence suggests, however, that a significant difference in dip might exist throughout the area.

Detailed measurements of S_2 in an overturned syncline in the central zone indicates a mean dip of 56° SW for the overturned limb, and 68° SW for the normal limb, a 12° difference. In the Old Fort Point Formation of the Muhigan Creek Anticlinorium (Figure 34), S_2 on the overturned limb dips about 35° SW whereas on the normal limb the average dip is 70°, a difference of 35°. Charlesworth and Evans (1962, p. 356-358) observed in the Jasper Anticlinorium that slaty cleavage on northeast or overturned limbs had a modal dip of 50° SW; on normal dipping southwest limbs the modal dip was 70° SW, a difference of 20°. They also plotted the dip of S_1 against the dip of S_2 for a number of localities. Recognizing that the dip of S_2 was strongly influenced by the presence of compentent beds, they selected data from slates as devoid of competent strata as possible. They found that the dip of cleavage increased at the rate of about 2° for every 10° increase in dip of bedding to the southwest. It decreased at approximately the same rate for beds dipping to the northeast. A plot of S_2 dip against S_1 dip in the Meadow Creek Anticlinorium (Figure 36) fails to indicate such a relationship. This is not unexpected in view of the more erratic sampling imposed by the poorer outcrops.

It can be concluded, therefore, that throughout the Jasper area slaty cleavage in the Old Fort Point Formation is arranged in a "fan-like" manner. The steeper dips are usually, but not always, located in the southwest limbs of folds. Lesser dips are

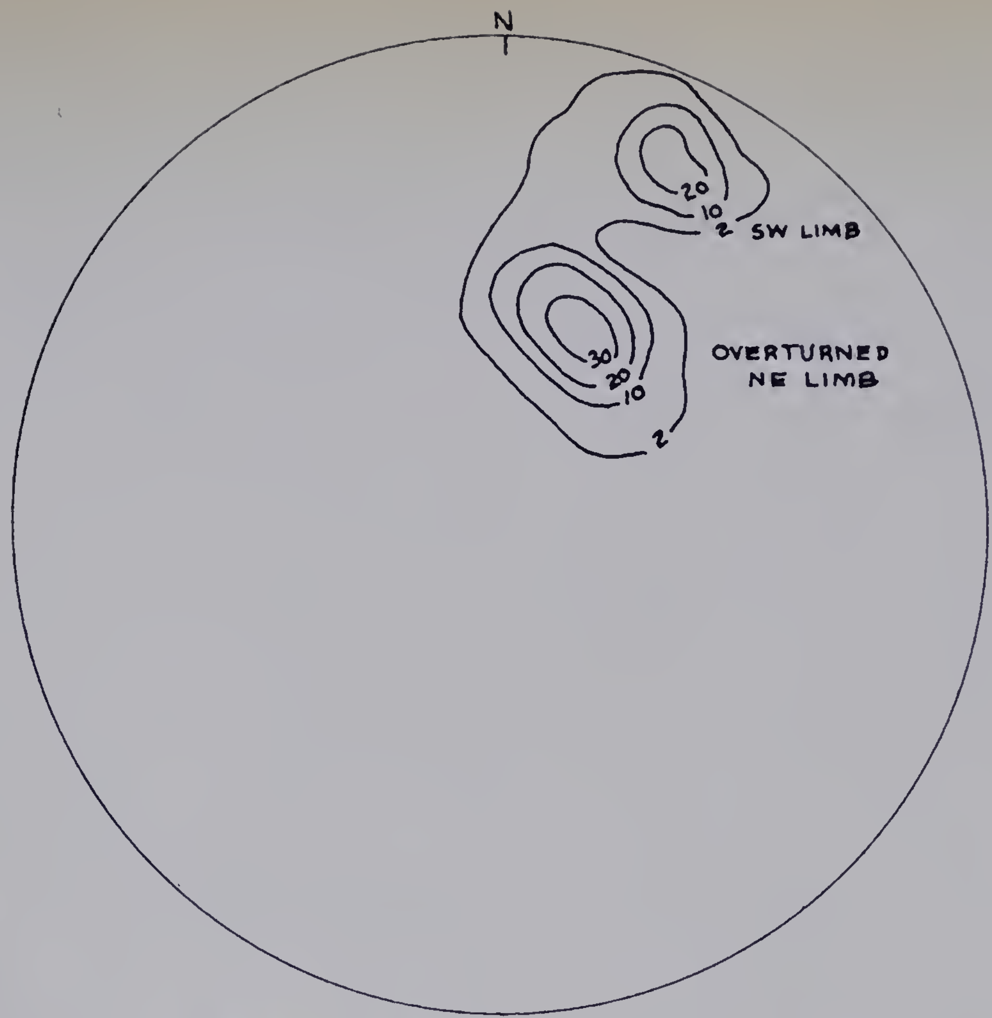


Figure 34 Contoured equal-area projection showing the distribution of poles to 61 S_2 planes in the Old Fort Point Formation of the Muhigan Creek Anticlinorium.

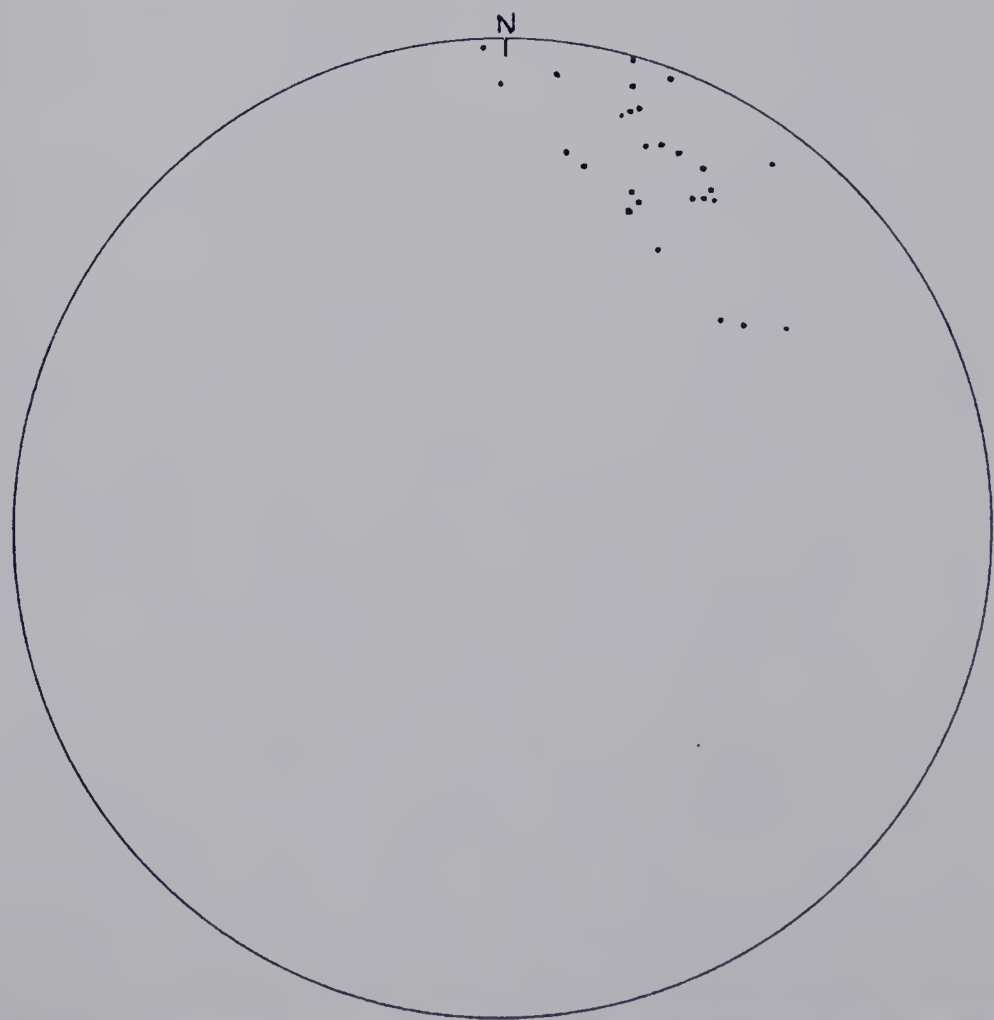
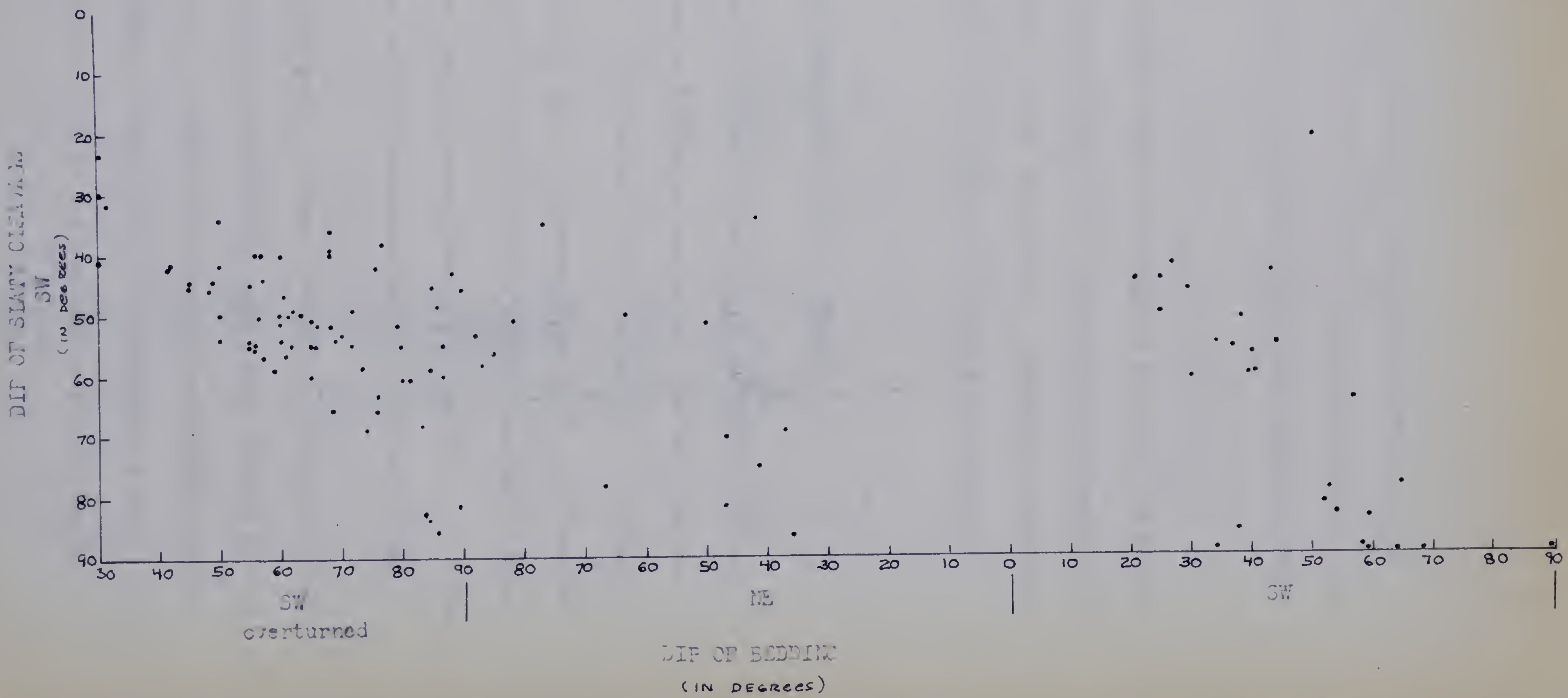


Figure 35 Equal-area diagram showing the orientation of 27 poles to S_2 planes in the Wynd Formation of the southwest limb - folded belt, Meadow Creek Anticlinorium.

Figure 36 Dip of Slaty Cleavage vs. Dip of Bedding in Meadow Creek Anticlinorium



found in the northeast (often overturned) limbs. Slaty cleavage, therefore, is not necessarily parallel to the axial surfaces of the folds. In some overturned folds, none of which are isoclinal, slaty cleavage has been observed to parallel bedding in the overturned limbs.

S_2 strikes parallel to the strike of the axial surfaces of the folds in the folded belt of Wynd strata that lies to the southwest of the central zone of the Meadow Creek Anticlinorium. The average strike is N 60° W to N 80° W, a difference of about 20° when compared to the strike of S_2 in the central zone, testifying to the relatively upright nature of the folds.

X-Ray Investigation of Preferred Orientation of Mica in Slates

The orientation of mica in slates was studied by X-ray diffraction techniques. This approach was necessary because the fine-grained nature of the rocks precluded study by optical universal stage. The objectives of this study were: (1) to obtain quantitative values for the degree of slaty cleavage development, (2) to see whether slaty cleavage differs from one place to another within a fold, (3) to check on the presence or absence of regional trends in cleavage development, and (4) to test whether any relationship exists between cleavage development and K-Ar radiometric dates.

Sample Collection and Preparation Fourteen oriented samples were collected. Thirteen of the samples were muscovite-chlorite slates and phyllites collected between Jasper and Yellowhead Lake. The fourteenth sample was a muscovite-biotite phyllite from the Mount Robson area (Table 9). All but three of the samples were dated. The three undated slates were from the limbs and hinge zone of an overturned syncline

TABLE 9: Results of X-ray Orientation Study of Slates and Phyllites

Sample Number	Formation	Distance from Jasper	Attitude of Bedding (S_1)	Attitude of Cleavage (S_2)	Dihedral Angle between S_1 and S_2	Orientation Index S_1	Orientation Index S_2	Area Ratios S_2/S_1	Area Ratios $\frac{S_2}{S_1+S_2}$
AK-376	OFP	1.4 miles E	N42°W/38°SW	N50°W/72°SW	34°	0.057	0.113	1.41	0.58
AK-377	Wynd	1.0 miles W	N90°W/85°SW	N90°W/85°SW	0°		0.072		
AK-370	Wynd	2.8 miles W	N73°W/79°SW	N73°W/79°SW	0°		0.061		
AK-375	Wynd	4.3 miles W	N63°W/43°SW	N65°W/65°SW	22°	0.070	0.080	1.56	0.61
AK-374	Wynd	5.0 miles W	N25°W/49°SW	N60°W/55°SW	30°	0.053	0.117	2.93	0.75
AK-373	Wynd	6.0 miles W	N50°W/70°SW	N62°W/74°NE	38°	0.034	0.159	1.80	0.65
AK-373	Wynd	7.7 miles W	N36°W/50°SW*	N36°W/52°SW	0°		0.065		
AK-662	OFP	7.9 miles W	N45°W/65°SW*	N45°W/65°SW	0°		0.158		
AK-371	Wynd	10 miles W	N32°W/51°SW	N82°W/85°NE	64°	0.035	0.104	2.43	0.71
AK-663	OFP	20 miles W	?	N50°W/30°SW	?		0.083		
AK-661	Miette (?)	50 miles W	horizontal	N60°W/90°	90°	0.000	0.075	24.0	0.96
Syncline: Normal limb	OFP	8.2 miles W	N27°W/36°SW	N47°W/52°SW	27°	0.079	0.086	3.6	0.72
Syncline: Hinge Zone	OFP	8.2 miles W	N76°W/37°NE	N36°W/59°SW	90°	0.000	0.046	20.7	0.95
Syncline: Ovt. limb	OFP	8.2 miles W	N40°W/73°SW*	N49°W/66°SW	13°	0.066	0.027	2.1	0.67

* Indicates overturned beds

(Old Fort Point Formation) in the central zone of the Meadow Creek Anticlinorium. Slices parallel to bedding and parallel to cleavage were cut from each sample. In samples where cleavage and bedding are parallel, only a single slice was cut.

Universal Stage The oriented slices were scanned in a motor driven universal stage designed for use with a Norelco X-ray Diffraction Unit (Evans, 1961). Cu radiation with $\lambda = 1.5405 Å$ was utilized. The universal stage was initially oriented so that the surface of the rock slice was at an angle θ to the X-ray beam; the geiger counter detector was set at an agle equal to 2θ. To avoid interference from quartz reflections, the 2θ chosen was 45.47°, and the reflecting plane of the muscovite was therefore 00,10. With the rock slice oriented in the position described, reflections occur from all muscovite flakes oriented parallel to the surface (S_1 or S_2) of the sample. By maintaining the 2θ value at 45.57° and changing the orientation of the sample, it is possible to detect variations in the amount of mica having a given orientation within the slice. These variations will be evidenced by changes in the intensity of the reflected X-ray beam. Because the universal stage has both a tilt and rotation axis (Figure 37), it is possible to construct the central portion of a petrofabric diagram illustrating the mica orientation in each sample slice. A diagram was prepared for each slice. The surface of each slice was considered to be horizontal.

Operating Conditions and Reproducibility of Results Operating conditions were standardized to insure reproducibility of results. Power setting of 35 Kv and 15 MA were employed and the multiplier and time constant maintained at setting of 1 and 8 respectively. Runs were never made on samples until the recorder and X-ray tube had been operating for one-half hour. It was found that sample slices could be removed from the universal stage

(001) had most horizontal [illegible] in the Douglas Creek [illegible] some parallel to bedding and [illegible] [illegible] samples where cleavage and bedding [illegible]

Universal Stage. The universal stage [illegible] was designed for use with a Norelco X-ray Diffractometer [illegible] 1961). Co radiation with $\lambda = 1.79$[illegible] was utilized. The universal stage was initially adjusted so that the surface of the rock slice [illegible] an angle [illegible] the [illegible] counter [illegible] an angle equal to 2θ. To avoid interference with other reflections, the 2θ [illegible] and the reflected [illegible] With the rock slice oriented in the position described, reflections occur from all muscovite [illegible] parallel to the surface (S_1 or S_2) of the [illegible]. By maintaining the 2θ value at [illegible] and changing the orientation of the sample, it is possible to observe variations in the amount of mica having a given orientation [illegible]. These variations will be illustrated by changes in the intensity of the reflected X-ray beam. [illegible] has been [illegible] (Figure [illegible]), it is possible to [illegible] sample [illegible] a diagram was prepared for each slice. The position of each slice was considered to be horizontal.

Operating Conditions and Reproducibility of Results. Operating conditions were standardized to insure reproducibility of results. [illegible] of 25 kV and [illegible] [illegible] and the slit [illegible] of 1° and ½° [illegible]. These were [illegible] samples [illegible] had been [illegible] completely [illegible]. It was found that samples [illegible]

Figure 37

Schematic Diagram Illustrating Universal Stage Used in Orientation Studies of Slates and Phyllites

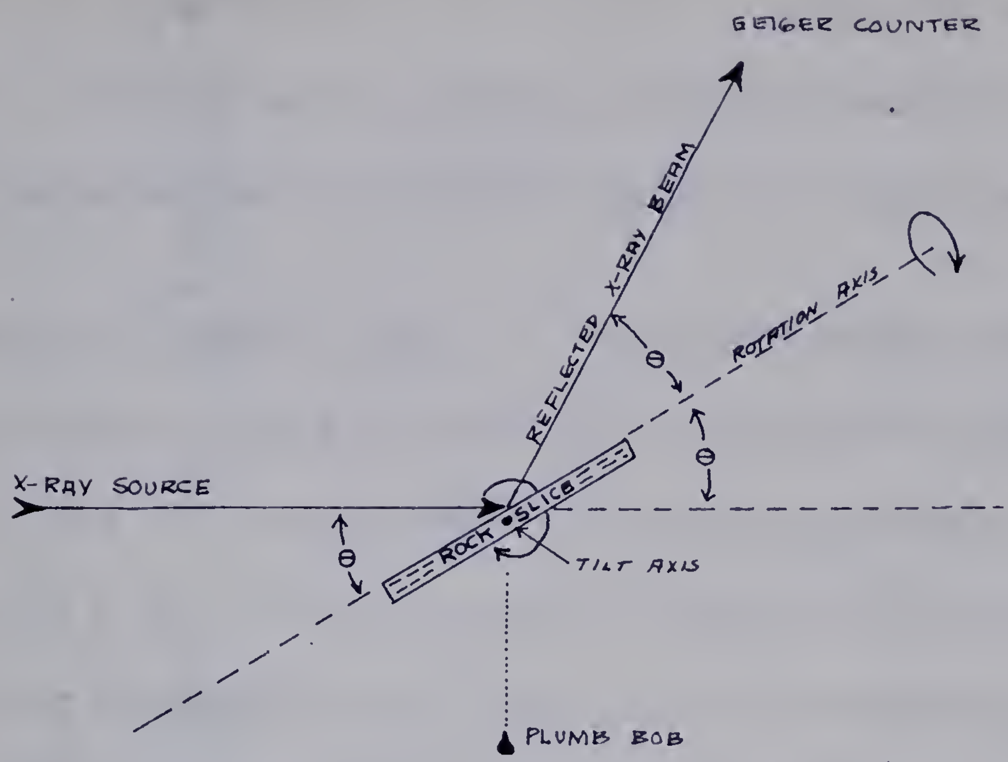
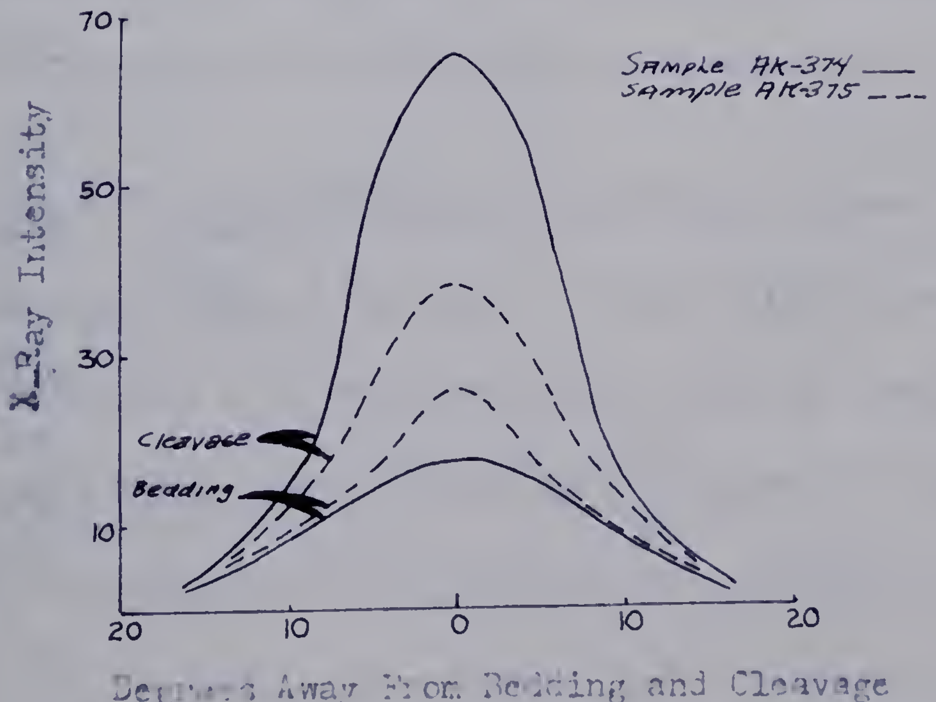


Figure 38

Examples of Profiles Used to Calculate Orientation Indices of Bedding and Cleavage Micas in Slate and Phyllite Samples



The cleavage and bedding orientation indices for samples AK-374 and 375 are 0.117 and 0.053, and 0.180 and 0.070, respectively

and replaced without affecting the intensity value. As a check on reproducibility, two different samples were scanned on three consecutive days; the results compared favorably. As a further check, each day that runs were made, a "standard" slice was placed in the stage and scanned briefly to detect any significant variations from the previous runs.

Correction of Intensity Values If a sample with perfect random orientation was scanned in different positions, the intensity of the reflected beam would vary considerably. This is the result of: (1) changes in the area of the slice irradiated as the angle of the specimen surface to the incident X-ray beam is changed, and (2) absorption of X-rays. A simple method was evolved for correcting all observed intensities so that the corrected intensity would be proportional to the relative number of hkl planes at each position.

A number of samples were scanned in the universal stage with the geiger counter detector set at a 2θ value which, while close to the 45.57° 2θ used above, was far enough away that only "background" radiation was being received. The variation in observed intensity for different sample positions was noted and correction factors derived so that identical intensity values would be obtained for all positions. Since these correction factors agreed with Field and Merchant's (1949) theoretically calculated values, they were adopted and used to correct all observed intensity measurements.

Calculation of Orientation Indices The petrofabric diagrams were used to obtain a quantitative measure or index of the degree of orientation of muscovite in each sample. Using the method suggested by Silverman and Bates (1960), an orientation index was calculated by using the Chi-square statistical test. The orientation index increases with increasing relative degree of orientation of mica in and near a given plane.

Profiles were drawn through the center of each petrofabric diagram (Figure 38). The profiles were then divided into 14 classes, each class represented by the column of a histogram whose height was proportional to the intensity of the X-ray reflection at the mid-point of each class. The mid-point intensities (X) were summed and then divided by 14 to determine the expected value ($\bar{X}$). The absolute difference between each observed value and expected value was squared $\left[(X-\bar{X})^2\right]$, and the chi-square value for the profile was found by dividing the sum of the squared differenced $\left[\sum (X-\bar{X})^2\right]$ by the expected value ($\bar{X}$).

The chi-square value is dependent on the shape of the profile, and the area underneath it, the latter being a function of the quantity of reflecting mica present. By dividing the chi-square value by the area underneath the curve, an orientation index is obtained which is independent of the amount of mica in the sample. In this way, samples with different amounts of mica may be compared.

In samples in which S_1 and S_2 are oblique, orientation indices were derived for both surfaces. In addition, the relative "amounts" of mica in S_1 and S_2 were calculated for purposes of comparison.

Results The results of the orientation study are shown in Table 9.

Observations and Conclusions When attempting to evaluate slaty cleavage development, both the orientation index of mica in S_2 and the relative amounts of mica in S_2 and S_1 must be considered. No direct correlation appears to exist between these two criteria; if two samples are compared, one may have a higher orientation index but a smaller proportion of mica oriented in the cleavage. In spite of these considerations

a number of observations and conclusions appear to be warranted.

(i) Amount and Orientation of Mica in S_1 and S_2 - From the viewpoint of the amount of mica parallel to an s-surface, slaty cleavage in slates is a much more important penetrative planar discontinuity than bedding (Table 10). In an average sample of slate or phyllite, two thirds of the mica is oriented within 15° of the cleavage plane and the remainder within 15° of the bedding. In two samples 90 percent or more of the mica is parallel or subparallel to the cleavage. Slaty cleavage is so well developed that in the event of subsequent deformation of the slates, it would have more of an influence on the resulting structures than would bedding. This can be observed in the formation of kink folds described below.

TABLE 10: Summary Results of Slate and Phyllite X-ray Orientation Studies

	Bedding	Slaty Cleavage
Average* amount of "total" mica in samples oriented parallel to plane	33%	67%
Range	5-42%	58-95%
Average* orientation index values	0.057	0.094
Range	0.000-0.079	0.027-0.159

* Note: Averages do not include two samples in which 90 percent or more of mica is oriented parallel to S_2.

Mica lying in the cleavage has a better preferred orientation than mica still oriented in the bedding. In nine of the samples where S_1 and S_2 are oblique, the orientation index for S_2 was greater than that for S_1; average values are 0.094 and 0.057

respectively (Table 10). In the one "anomalous" sample (from the overturned limb of the syncline suite), the orientation indices may be misleading. The dihedral angle between S_1 and S_2 in the samples is only 13° and some of the cleavage mica may actually have been contributing to the bedding value.

(ii) Regional Variations in Slaty Cleavage Development - No regional trend of slaty cleavage development is evident in the data from this study (Table 9) in spite of the fact that radiometric dating evidence and mineralogical variations attest to a westward increasing grade of regional metamorphism. Other controlling factors, to be discussed below, appear to have had a greater influence on the cleavage development.

(iii) Effect of Original Grain Size and Mineralogy on Cleavage Development - Samples AK 372 and 662 (Table 9) were collected only a short distance apart on the overturned northeast limb of the Meadow Creek Anticlinorium. They were presumably exposed to a similar tectonic and metamorphic environment. Sample AK 372 is a very silty, sandy slate from the Wynd Formation; AK 662 is a very fine grained phyllite from the Old Fort Point Formation that contains very little silt or sand-sized materials. The K_2O content of AK 662 is 2.5 times that of AK 372 indicating that the original clay mineral content of the latter sample may have been only half that of the Old Fort Point sample. The S_2 orientation index of the phyllite is 2.5 times as large as that of the more silty and sandy rock. This suggests that the finer grained, more argillaceous nature of the original sediment was a major controlling factor in the development of a preferred orientation of mica along the cleavage.

(iv) Variation of Cleavage Development with Structural Position - The position

of a sample within a developing fold also appears to be a significant controlling factor in the development of slaty cleavage. This seems to be particularly true with regard to the "amount" of micaceous minerals oriented in the cleavage. In the suite of samples from the overturned syncline, the sample from the hinge zone had 95 percent or more of the mica oriented parallel to the cleavage, whereas the limbs yielded lesser values of 72 and 67 percent. The hinge zones of similar folds in slates show a marked thickening with respect to the limbs (Figure 21). This marked thickening in the hinges may have required more extensive mechanical reorientation and recrystallization than the changes which took place in the limbs.

Fracture Cleavage

Occurrence Fracture cleavage is developed in the conglomerates, sandstones, siltstones and limestones of the Meadow Creek, Old Fort Point and Wynd Formations. Its development is sporadic compared to that of slaty cleavage in argillaceous rocks. Many outcrops of competent strata show little sign of fracture cleavage even though interbedded argillaceous rocks are well cleaved. In the Meadow Creek Anticlinorium, fracture cleavage is best developed in overturned limbs of folds.

Outcrop and Hand Specimen Description In a typical outcrop of arenite, fracture cleavage is seen as a series of parallel planes of parting which permeate the rocks. The planes of parting generally range from 2 to about 10 mm apart, but occasionally are up to 25 mm apart. The planes often display a slight sheen resulting from fine-grained muscovite and chlorite flakes oriented along them. Because the fractures usually detour around pebbles, the planes of parting are hackly, especially in the coarser grained rocks (Plate VI-4). Secondary quartz or calcite mineralization along fracture cleavage is rare.

In bedded limestones, fracture cleavage usually consists of fine fractures 5 mm or less apart which are coated with muscovite and chlorite.

Thin Section Description In fracture-cleaved arenites, fracture surfaces 2 to 10 mm apart separate domains in which there may be a large number of discontinuous and irregularly oriented fractures (Plate VIII-5). The large and small fractures have muscovite and chlorite aligned along them and usually pass around sand grains and pebbles rather than through them. The sand grains and pebbles have coats of fine-grained muscovite and chlorite wrapped around them and appear to "float" in a fine-grained matrix of muscovite, chlorite, calcite and silt-sized particles of quartz and feldspar.

Suturing of contacts between adjacent grains is uncommon; the large percentage of fine-grained matrix probably allowed the larger grains and pebbles freedom of movement during cleavage development, cutting down on the number of direct grain to grain contacts. Many of the inequidimensional sand grains and pebbles have their long dimension oriented parallel or subparallel to the cleavage. The larger sand grains and quartz pebbles invariably exhibit wavy extinction and have biaxial properties in basal sections. Boehm lamellae are common in some of the quartz grains (Plate VIII-7), but whether these were formed during deformation of the strata or inherited from the source terrain is not known.

An arenaceous rock which has not suffered the effects of fracture cleavage is illustrated in Plate VII-3.

In the finely crystalline limestones of the Old Fort Point Formation (Plate VIII-6), fracture cleavage consists of parallel fracture zones separating unfractured domains. The

fracture zones (or surfaces) are up to 0.5 mm wide, and along them are concentrations of muscovite and chlorite flakes. They are much straighter and smoother than the fractures in arenites because of the small, uniform grain size of the limestones.

Orientation of Fracture Cleavage and its Relation to Slaty Cleavage Fracture cleavage was not measured systematically because of its sporadic development. Its orientation was measured in a number of places for comparison with slaty cleavage and other fabric elements.

The strike of fracture cleavage usually parallels the strike of nearby slaty cleavage and thus approximates the strike of axial surfaces of the folds. The dip of fracture cleavage is very sensitive to changes in lithology and the attitude of the bedding and seldom does it parallel the dip of slaty cleavage or the dip of axial surfaces.

Fracture cleavage tends to form at a greater angle to bedding than slaty cleavage, regardless of the orientation of the associated axial surface. At contacts of argillaceous and arenaceous strata or in graded sequences, this refraction of cleavage is quite marked (Plate IV-5 and IV-6). In interbedded limestone, argillaceous limestone, and calcareous slate sequences a marked sigmoidal cleavage is formed, faithfully reflecting slight changes in lithology (Plate V-1). This refraction of cleavage has a strong influence on the overall dip of fracture and slaty cleavage in the two limbs of a fold. In an upright fold, fracture cleavage on both limbs dips at an angle less than that of slaty cleavage on the normal limb but dips at a lower angle on the overturned limb. In both folds a pronounced fanning of fracture cleavage results, the fans opening toward the convex surface of the folds.

Slip Cleavage or Strain-slip Cleavage

Slip cleavage is defined herein as a type of rock cleavage in which visible displacements have occurred along cleavage planes. The original sedimentary foliation between adjacent cleavage surfaces is commonly crumpled or folded. The finest examples of this cleavage type are found in the tight mesoscopic folds in interbedded limestones and slates of the Old Fort Point Formation.

Plates VI-1 and VI-5 show slip cleavage developed in interbedded limestone and slate. The cleavage consists of a penetrative set of fractures which closely parallel the axial surfaces of the folds. The fractures show only minor deviations as they pass through both limestone and slate. Visible displacements have occured along most of the fractures. The direction of relative movement is consistentexcept in the hinge zone where it is somewhat erratic. In the northeast limbs, the relative movement is comparable to that which occurs in reverse faults; in the southwest limbs, it is of normal fault type. Well-developed slickensides on the cleavage surfaces show that the slip direction was at right angles to the direction of the associated fold axes. These folds closely resemble the slip or shear fold model of Turner and Weiss (1963, p. 48) and others.

The slices between adjacent cleavage surfaces are 5 to 15 mm thick and are analogous, except in scale, to the "microli thons" of de Sitter (1959, p. 97). The slate portions of the slices have been strongly folded or crumpled, indicating shortening normal to cleavage and extension parallel to it. Micaceous minerals in the slate show a preferred orientation parallel to cleavage. In the limestone slices, folding has occurred but it is not as tight as in the slates.

In Plate V-4, the bedding surfaces of calcareous siltstones are characterized by a feature that resembles sedimentary ripple marks. This feature is formed by a crude fracture cleavage which dips in the same direction as the bedding but at a lower angle. Slip has occurred along the cleavage surfaces but the displacement is so variable that the irregular pattern develops. Folding in the siltstone between cleavage surfaces is minor when compared to the folds in limestone and interbedded slate.

Cleavage Mullions

Cleavage mullions are oblong slices of rock that form when fracture cleavage cuts through thin competent layers surrounded by relatively incompetent layers. The term "cleavage mullion was originally used by Wilson (1953) but de Sitter (1958, p. 279) later used the term "cleavage boudinage" to describe the same feature. The former term will be used herein for reasons of priority and because "boudinage" has a strong connotation of extension approximately at a right angle to the fold axis.

Charlesworth and Evans (1962, p. 358) used the term "cleavage boudinage" to describe features from the Old Fort Point Formation of the Jasper Anticlinorium formed when siltstones were split into small blocks and separated by bands of inflowing argillite. These structures are located on attenuated northeast limbs of anticlines.

Plate VI-6 illustrates cleavage mullions from the normal dipping southwest limb of the Muhigan Creek Anticlinorium. The strata involved are the interbedded relatively competent limestones and incompetent slates of Member B of the Old Fort Point Formation. Fracture cleavage has separated the originally continuous limestone bed into oblong slices 1 to 1.5 inches wide and 1.5 inches thick; the fractures are lined with muscovite and

In Plate IV-4, the bedding surfaces in [illegible] limestone [illegible] a feature that resembles slickensides [illegible]. This feature is formed by a [illegible] fracture cleavage which [illegible] in the limestone [illegible] the bedding but at a large angle. Slip has occurred along the cleavage surfaces but the displacement is so [illegible] the [illegible] pattern develops. Folding [illegible] between cleavage surfaces is [illegible] when [illegible] in the interbedded limestone and thin-bedded shale.

<u>Cleavage Mullions</u>

Cleavage mullions are oblong pillars of rock that form where fracture cleavage cuts through thin competent layers surrounded by relatively incompetent layers. The term "cleavage mullion" was originally used by Wilson (1953) and de Sitter (1956, p. 279) later used the term "cleavage boudinage" to describe the same feature. The former term will be used herein for reasons of priority and because "boudinage" has a strong connotation of extension approximately at a right angle to the fold axis.

[illegible] (1962, p. 388) used the term "cleavage boudinage" to describe features from the [illegible] Formation [illegible] formed when cleavage [illegible] thin [illegible] blocks and separated by bands of [illegible]. These structures are formed [illegible] of limestone.

Plate [illegible] illustrates cleavage mullions from the [illegible] of the [illegible] Creek [illegible]. The mullions [illegible] relatively competent limestone and incompetent shales of Member B of the [illegible]. Fracture cleavage has separated the originally continuous limestone bed into [illegible] 1 to 1.5 inches wide and 1.5 inches thick. The fractures are [illegible]

chlorite. The mullions have their long axis oriented roughly parallel to the axis of the fold.

The fracture cleavage cutting the competent beds is vertical to steeply dipping; slaty cleavage in the argillaceous layers dips southwest at a much lower angle. Displacements along the cleavage surfaces have the same sense of movement as that discussed in the section on slip cleavage. Gentle folding of marker horizons in the mullions indicates that they have been shortened in a direction normal to the cleavage and lengthened parallel to the cleavage.

Interpretation of Cleavage

Slaty Cleavage Slaty cleavage formed while the Old Fort Point strata were being and metamorphosed. It formed perpendicular to σ_1, by syntectonic crystallization of micaceous minerals and mechanical rotation of pre-existing platy minerals into the plane of cleavage. Slaty cleavage development was favoured in rocks with a high content of clay minerals. Shear often took place on cleavage planes after they had formed.

(i) *Evidence Indicating S_2 Formed Normal to σ_1* - The mechanical rotation of pre-metamorphic mineral grains (e.g. chlorite-muscovite books) into the plane of cleavage suggests that the cleavage plane was perpendicular to σ_1. The mechanical rotation was perhaps made easier by the development of abnormal pore-water pressures (Hubbert and Rubey, 1959) which would have significantly reduced internal friction. Maxwell (1962) has shown that some slaty cleavage may have formed almost entirely by mechanical rotation without associated crystallization of platy minerals.

The slaty cleavage on the convex sides of the small folds in Plate V-7 is "splayed".

Approaching the convex side of the folded sandstone bed, the maximum principal stress trajectories would be refracted until they are almost perpendicular to the convex side (Bell and Currie, 1964). Since the slaty cleavage reflects this refraction of stresses, it is reasonable to assume that it formed perpendicular to 6_1.

Charlesworth and Evans (1962) have found boudins of siltstone rotated toward the cleavage in Old Fort Point slates of the Jasper Anticlinorium. They also point out a number of examples of cleavage refraction that are compatible with cleavage forming perpendicular to 6_1.

(ii) Shear Along Slaty Cleavage - Small displacements of bedding laminae along S_2 are commonly observed throughout the area (Plate VIII-2). Slickensides are also seen along S_2 planes. These phenomena indicate that shear has taken place along cleavage planes at times when the cleavage was occupying positions not perpendicular to 6_1. Slip along S_2 appears to have been an important mechanism in the development of similar folds in the incompetent slates of the Old Fort Point Formation (see above).

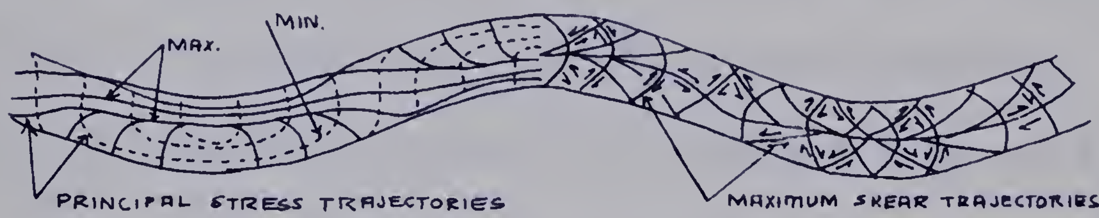
(iii) Origin of Fanning of S_2 - The "lag theory" states that in a developing fold the crystallization of mica in the plane perpendicular to 6_1, and the mechanical rotation of micaceous minerals into the same plane do not keep pace with the rotation of the limbs in which the cleavage is developing. When rotation of the limbs ceases, the cleavage will occupy an intermediate position relative to 6_1. Another possible explanation is that refraction of stress trajectories towards bedding, a common occurrence in more competent beds, causes the fanning throughout the fold. Since the nature of the fanning in most folds is compatible with either theory, it seems likely that both mechanisms were operating.

<u>Fracture Cleavage</u> Fracture cleavage formation is restricted to relatively competent strata such as sandstones and siltstones. It is clearly a shear phenomenon and did not form perpendicular to 6_1, as did slaty cleavage. The close association of fracture and slaty cleavage in folds (Plate IV-6) indicates that they both formed during the folding of the strata.

Fracture cleavage formed oblique to 6_1. Refraction of the maximum principal stress trajectories towards parallelism or subparallelism in competent units (Figure 39) gave rise to shear planes inclined at a high angle to the bedding surfaces. In some cases visible displacements have occurred along these fracture cleavage planes (Plate V-2).

The sigmoidal nature of some fracture cleavage surfaces merely reflects gradational variations in the competency of the strata being fractured (Plate V-1).

FIGURE 39 DISTRIBUTION OF PRINCIPAL STRESS TRAJECTORIES AND MAXIMUM SHEAR TRAJECTORIES IN A "COMPETENT" BED BEING FOLDED. MODIFIED FROM BELL AND CURRIE (1964).



Kink Folding

Description

Kink folds have been observed only in the Meadow Creek Anticlinorium and in a few outcrops in the Yellowhead Lake Anticlinorium. They are mesoscopic structures composed of two limbs; (1) a kinked zone, and (2) an intervening zone. The kinked zone, bounded by parallel S_3 surfaces, is a narrow zone in which the cleavage planes (S_2) are visibly rotated (Plate V-3 and Figure 41). In the wider intervening zone where the cleavage has not been kinked, it retains its original orientation. The S_3 surfaces are the axial surfaces of the folds and the intersection of S_3 with S_2 forms the fold hinges. The kink folds are monoclinal and plane cylindrical. Bedding (S_1) is also offset by the kink folding but it did not play a significant role in the fold development. Because the kink folds clearly postdate the F_1 folds, they have been designated F_2 folds. Similar structures have been variously referred to as "Knickzone" (Hoeppener, 1955, p. 34) and "Flexuren" (Hoeppener, 1956, p. 268).

Poles to S_3 surfaces scattered throughout the Meadow Creek Anticlinorium are plotted in Figure 40. The strike of the S_3 surfaces is variable (N 30° W to N 90° W) but they dip consistently toward the north and east. Southwest dipping S_3 surfaces have not been observed. The attitudes of S_3 surfaces vary within a single outcrop; differences in dip up to 10° are not unusual and kink folds can be seen to cross one another. The L_{2x3} lineations plunge toward the northwest.

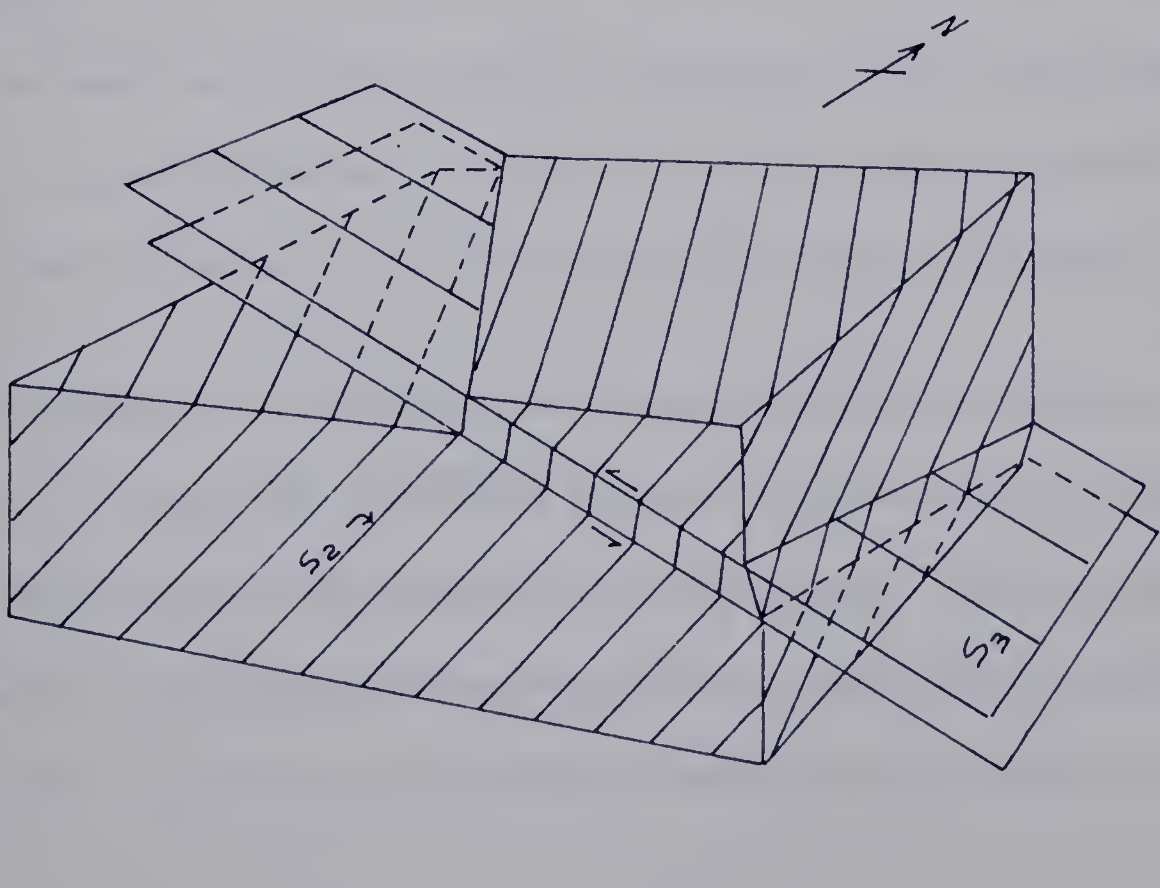
With one exception, the apparent sense of movement in the kinked zones is

Figure 40 Equal-area projection showing the orientation of (1) poles to 35 S_3 surfaces (·) and (2) 13 L_{2x3} lineations (x) in the Meadow Creek Anticlinorium. Dashed circle outlines maximum concentration of S_2 planes in the Meadow Creek Anticlinorium.

Figure 41 Diagrammatic block showing relations of slaty cleavage (S_2) and kink fold boundary surfaces (S_3) in areas of F_2 kink folding.

Figure 40

Figure 41



uniform throughout the Meadow Creek Anticlinorium (Figures 41 and 42). The upper S_3 surface of a kinked zone has moved updip relative to the lower S_3 surface. The southwest dipping cleavage has been rotated counterclockwise toward the vertical. The angle of rotation varies from less than 10° to more than 40°. In one outcrop, near a normal fault, the sense of movement was observed to be the opposite of that described above. In the small number of examples seen in the Yellowhead Lake area, the sense of movement was similar to that throughout the Meadow Creek area.

In many instances, the S_3 boundary surfaces are merely thin zones of sharp bending of the cleavage (Plate V-4). In some cases, the S_3 surfaces are fractures but it is difficult to prove conclusively that they were shear surfaces when the kink folds were developing. Veining along S_3 surfaces is uncommon.

The width of the kinked zone varies from less than 3 mm to more than 100 mm. The distance between adjacent kink zones is usually greater than the width of the zones themselves and varies from less than 6 mm to more than 1.5 meters. Individual kink folds can be seen to extend along outcrops for distances of up to 40 feet or more although most die out in shorter distances. Although no quantitative data is available, it appears that the wider the kink zone, the smaller the angle of rotation of cleavage.

The spacing of kink folding appears to be controlled by the lithology of the country rock. In Figure 43, the distance between kinked zones has been plotted against lighology for 15 exposures of Old Fort Point and Wynd strata. With increasing micaceous mineral content, the kinked zones become narrower and more closely spaced (Plates V-4 and V-6). Thus, although kink folds have been observed in fracture-cleaved silt-

Figure 42 Two-dimensional schematic representation of movements taking place during formation of a typical F_2 kink fold. Angle of rotation of S_2 is α. Note vertical extension and horizontal contraction resulting from kink folding.

Figure 43 Minimum and maximum distances separating adjacent kinked zones in rocks of different lithology at 15 localities in the Meadow Creek Anticlinorium.

Figure 42

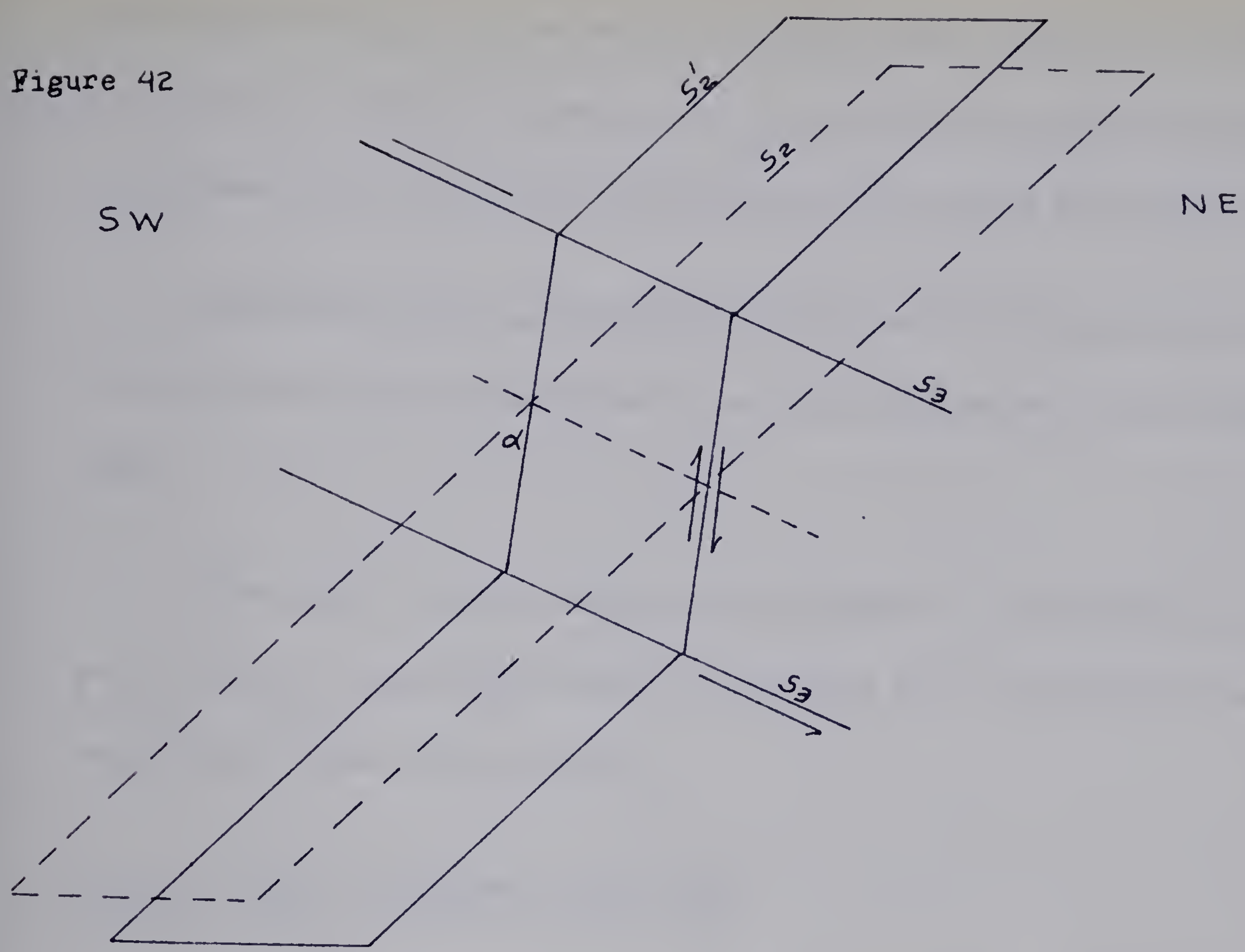
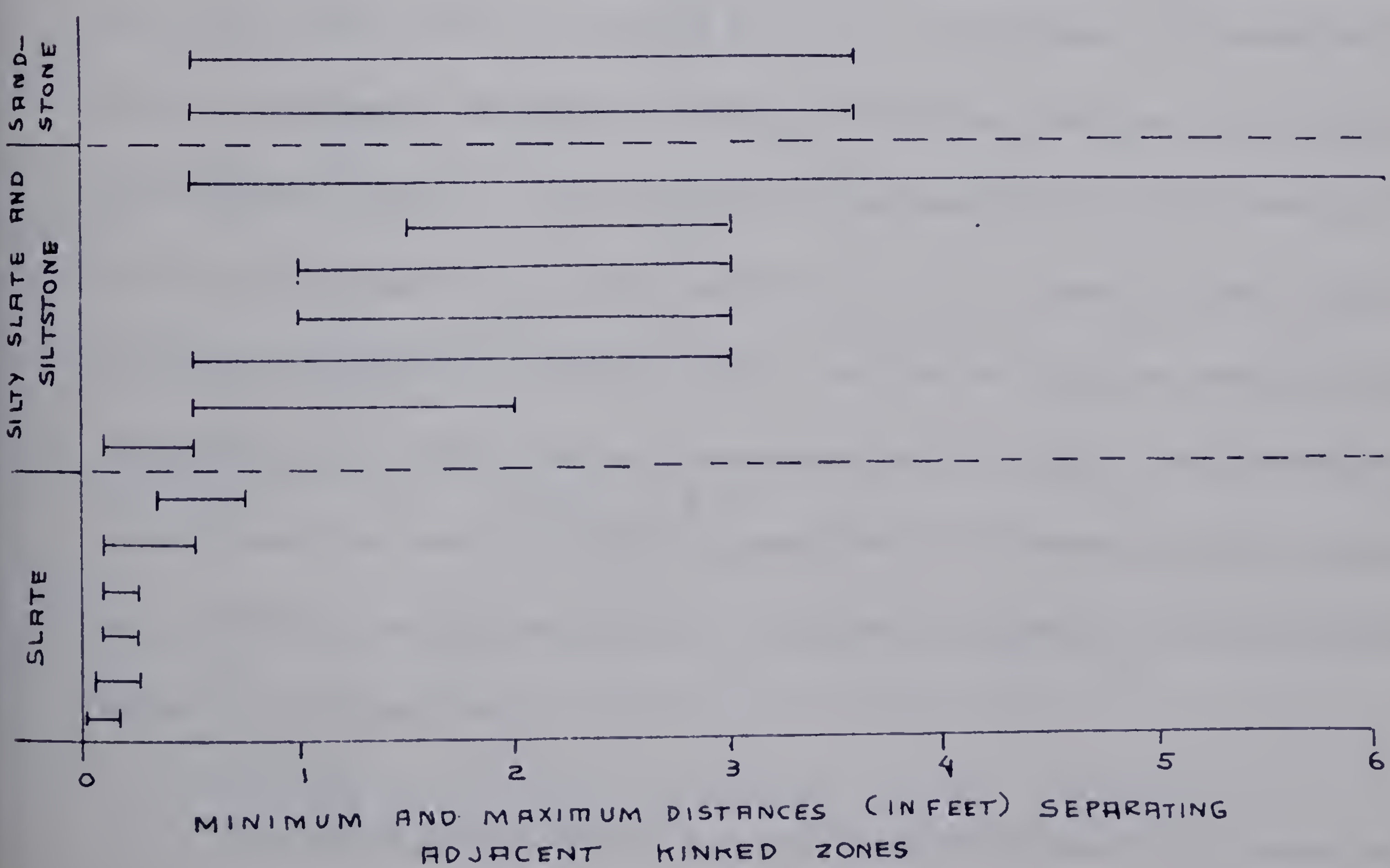


Figure 43



stones and sandstones, they are narrower and more closely spaced in well cleaved slates and phyllites. In the latter types of rocks, they may be so narrow and closely spaced as to constitute a discontinuity that is penetrative on the scale of the outcrop (Plate V-5).

Examination of thin sections (Plate X-1) of small kink folds so far has failed to show that the crumpling in the kinked zones was any greater than in the intervening limbs.

What appear to be microscopic kink fold domains in mica flakes and calcite grains have been recognized in thin sections of some Old Fort Point slates and joint vein fillings (Plates VIII-3 and X-2).

Effect and Time of Formation of Kink Folds

From Figures 41 and 42, it is readily apparent that the overall effect of the kink folding has been horizontal contraction and vertical extension. The amount of contraction and extension varies from outcrop to outcrop, but increases with increases in the width of the kinked zones, the angle of rotation of the kinked cleavage, and the spacing of the kink folds. Poor outcrops and sporadic development of kink folds prohibited quantitative measurements of contraction and extension in the Meadow Creek Anticlinorium, but the work of Zandvliet (1960, p. 87) in the Pyrenees has given some idea of the magnitude of deformation that can be achieved by kink folding. He estimated that in a 9,000 meter traverse, kink folding accomplished a 300 meter horizontal extension and a 415 meter vertical contraction. The sense of movement in his area is opposite to that in the Jasper area.

The uniformity of attitude and generally consistent sense of movement indicates

kink folds formed under a uniform set of stresses during a single episode of deformation. It is clear that they developed after the main episode of folding and metamorphism that affected the Meadow Creek Anticlinorium. Kink folds deflect cleavage and in some outcrops penetrate completely through mesoscopic F_1 folds without any sign of being distorted. It is also clear that they did not form at the same time as the normal faults; the latter involved horizontal extension and not contraction. Whether the kink folding occurred before or after the normal faulting is not evident. In no outcrop could it be seen that the normal faults displace the kink folds or that the folds pass uninterruptedly through the faults.

It is not clear when the "anomolous" kink folds, those in which the sense of movement is opposite to that in the majority of folds, actually formed. If we assume that all the kink folds formed prior to normal faulting, then the stresses responsible for the faulting may locally have caused normal fault type movement along pre-existing S_3 surfaces. The kinked cleavage would at this time be rotated in a clockwise direction facing north. On the other hand, these kink folds could have initially formed during the episode of normal faulting and thus be older or younger than the majority of kink folds. A third possibility is that the clockwise rotation of cleavage is a result of relatively recent creep.

Origin of Kink Folds in the Jasper Area

Laminar gliding on S_2 coupled with external rotation of S_2 appears to have been the principal mechanism by which the kink folds developed. The kink zone boundary surfaces (S_3) are thus strain discontinuities which define the limits of deformation by

gliding. The greater frequency of kink folds in argillaceous strata illustrates the importance of a well-developed cleavage in the formation of such folds. Kink zones that have been produced artificially in single crystals and in phyllites also are thought to have been formed by laminar gliding (Turner and Weiss, 1963).

An alternative explanation is that the S_3 surfaces were surfaces of active shear and that movements along them caused kinking of the cleavage in the narrow zones between adjacent S_3 surfaces (Ramsay, 1962). Because slickensides were not observed on any S_3 surfaces in the Jasper area, this explanation is considered unlikely. Although the S_3 surfaces in some outcrops are presently surfaces of fracture, the fractures probably developed after the kink folds formed.

<u>Kinematic and Dynamic Interpretation of Kink Folds</u>

The well-developed cleavage in the Old Fort Point and Wynd Formations made the rocks mechanically anisotropic. Sometime after the episode of major folding and either before or after the formation of the normal faults, the Jasper area was exposed to a stress system that caused local development of kink folds. This stress system may have been related to the main orogenic system. The horizontal contraction achieved by the kink folding and the attitude of the S_3 surfaces indicates that 6_1 was compressive by nature, probably subhorizontal, and directed in a northeast-southwest direction.

In some areas of the world where kink folds are present, they exist as conjugate sets. In the Jasper area, only a single set developed. Paterson and Weiss (1962) found that in phyllites stressed at 25° to 45° to S_2, only one set of kink folds formed.

The kink fold development probably took place over a short period of time compared to that necessary to form the F_1 folds; the rocks were presumably more viscous during kink fold development. Metamorphism does not appear to be associated with the formation of the kink folds.

Jointing

Five hundred and fifty joints were measured in the Meadow Creek Anticlinorium. Most of the measurements are from the Old Fort Point Formation, a smaller number from the Wynd Formation. Measurements were confined to the northeast limb and central zone of the anticlinorium.

Geometric Classification of Joints

The geometric classification used in this discussion is illustrated in Figure 44.

Morphology and Veining of Joints

In general, joint surfaces are not well exposed in the Meadow Creek Anticlinorium. Joints which have been interpreted as shear joints (Table 11), are generally large, planar, and have smooth surfaces, some of which bear slickensides. Extensional joints, on the other hand, tend to be smaller and very rough in appearance. The spacing of joints appears to be related to the thickness and lithology of the beds. Joints are more closely spaced in thin siltstone or sandstone beds and farther apart in the slates and massive sandstones.

About 30 percent of the joints measured have vein fillings. Every joint set contains some veined joints. Quartz, calcite, chlorite and siderite are the minerals present. Individual veins range in thickness from less than one-quarter inch to more than one inch. The lithology of the country rock appears to have exerted some control on the mineralogy of the vein fillings. Veins in slates (which are commonly calcareous) are predominantly calcite, whereas those in sandstones and conglomerates are largely

Figure 44 Relationship between fabric axes, joints and folds.

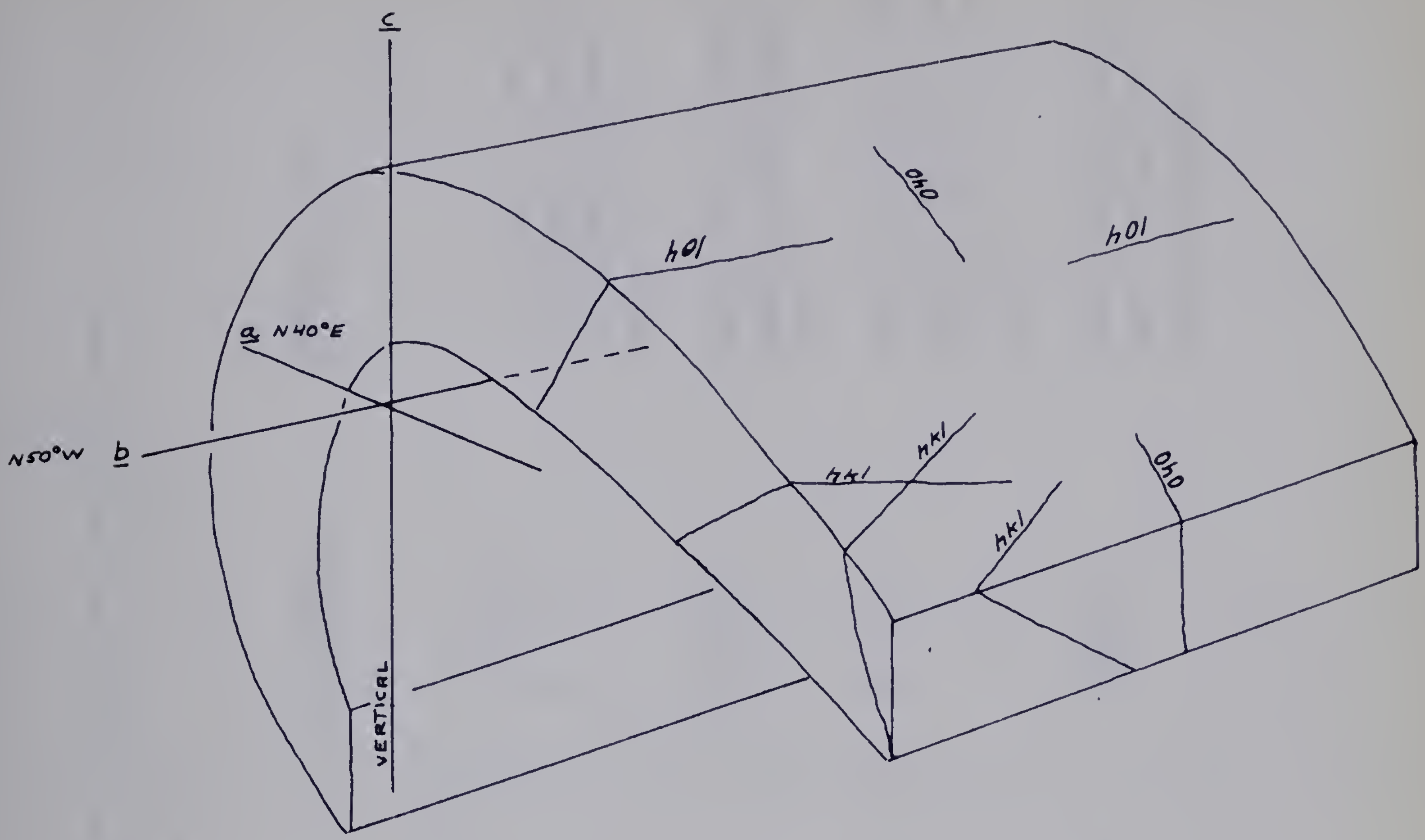


Figure 45 Rose diagram showing strike of 545 joints in the Meadow Creek Anticlinorium.

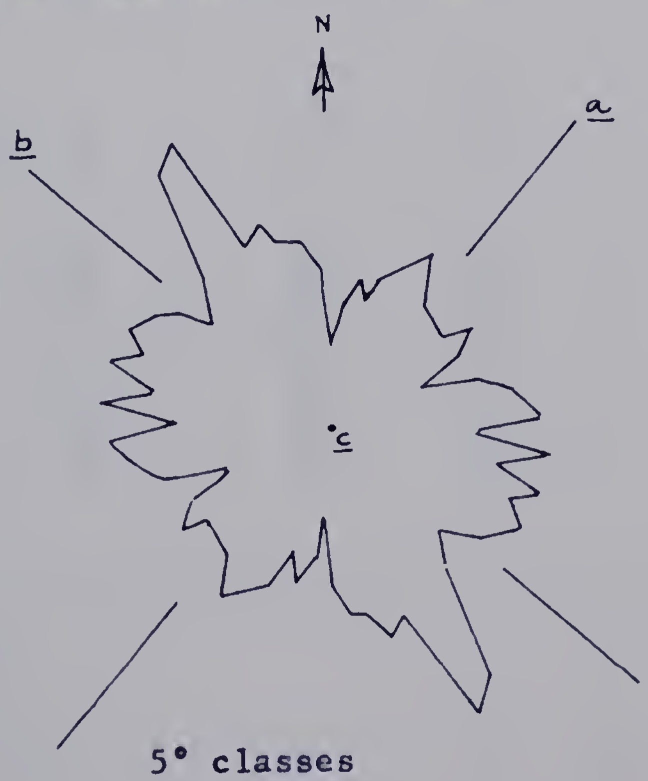


TABLE 11: Classification and Description of Major Joint Sets in Meadow Creek Anticlinorium

Joint Set	Orientation	Classification		Significance	Characteristics
		Geometric	Genetic		
1	N25°W/40°NE	hkl	Shear	Local (?)	Large, planar, smooth surfaced, occasionally veined and slickensided; common in slate and arenite.
2	N85°W/40°SW	hkl	Shear	Local(?)	Large, planar, smooth surfaced, rarely veined; common in slate.
3	N45°E/70°SE-	OhO	Extension	Regional	Small, very rough, strike varies considerably, veined and unveined; common in arenite.
4	N65°W/75°NE	hOl	Extension	Regional	Small, rough, straight, rarely veined; common in slate and arenite.

quartz with minor amounts of calcite.

The vein quartz shows evidence of shearing and extreme strain. The vein calcite has twin lamellae which are often curved and, in some cases, even kinked (Plate X-2). This indicates that the rocks experienced some deformation after the vein material was emplaced.

Geometric Analysis

Figure 45 is a rose diagram showing the strike of the joints. The density distributions of all measured joints are shown in Figures 46, 47 and 48. The relatively low concentrations of the maxima cast doubt on their significance. As a check, plots were made of the joints from a small number of outcrops where lithology and dip were uniform and where joints were relatively well developed. The joints from these outcrops exhibited marked concentrations similar to those in the larger sample in which lithology and dip of the strata were not so uniform.

Four joint sets, two hkl sets, one h01 set and one 0h0 set can be recognized in the Meadow Creek Anticlinorium. The orientation and characteristics of each set are summarized in Table 11 and their positions relative to the fabric axes are shown diagrammatically in Figure 48.

In view of the complexity of the jointing in the area no interpretation will be attempted.

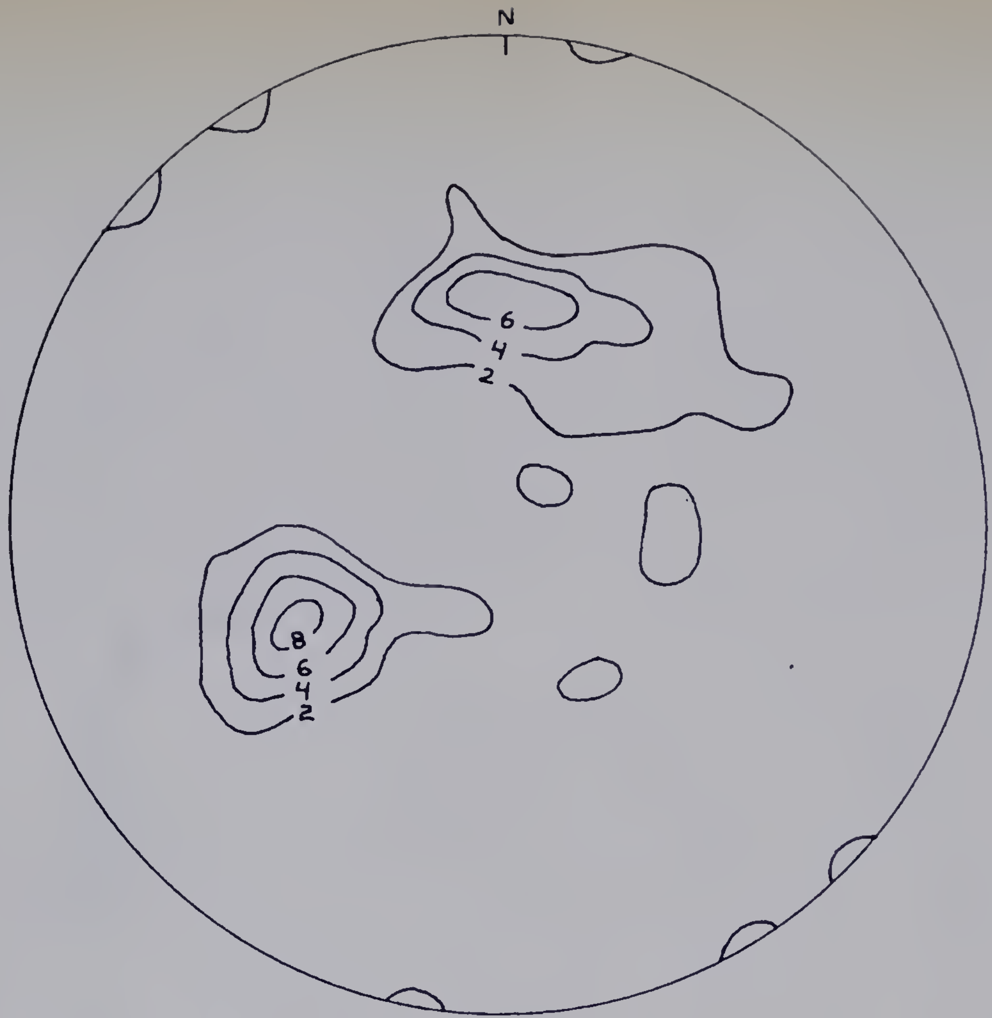


Figure 46 Contoured equal-area projection showing the distribution of poles to 365 joints in the northeast limbs of folds in the Meadow Creek Anticlinorium.

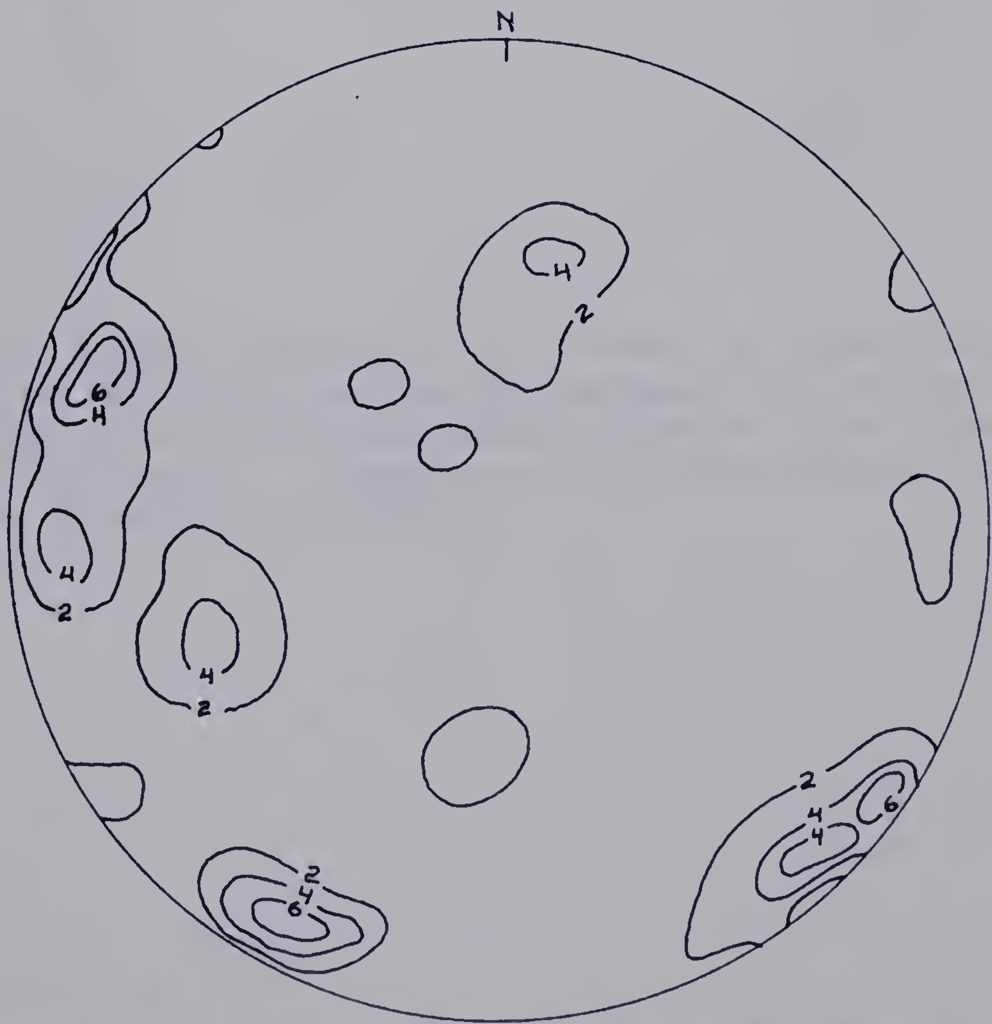


Figure 47 Contoured equal-area projection showing the distribution of poles to 180 joints in the southwest limbs of folds in the Meadow Creek Anticlinorium.

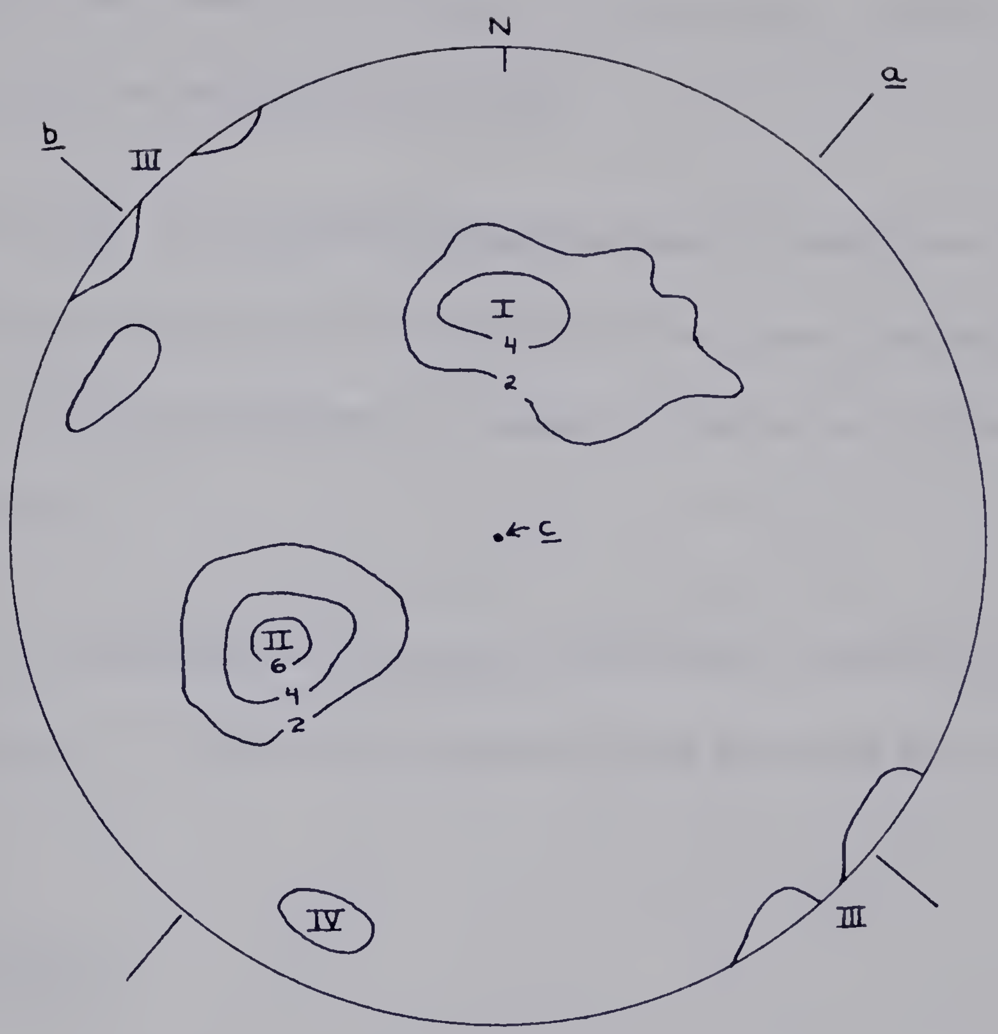


Figure 48 Contoured equal-area projection showing the distribution of poles to 545 joints in both the northeast and southwest limbs of folds in the Meadow Creek Anticlinorium. The fabric axes are a , b and c . Roman numerals denote different sets of joints referred to in Table .

Faulting

Faults were located in the field either from actual exposures or from relations exhibited by adjacent strata. The distinctive, persistent lithologies within the Old Fort Point make for easy recognition of faults in that formation. In the Wynd Formation, faults are obscure and may go unnoticed.

Normal faults, reverse faults and localized zones of décollement are present in the Meadow Creek Anticlinorium. Normal faults are numerous especially in the central zone, whereas reverse faults are uncommon. Displacements along faults are moderate to small.

The zones of décollement and reverse (thrust) faults formed during the main episode of folding, D_1. Normal faults probably formed some time after folding had ceased.

Zones of Decollement

Zones of intense folding and shearing have been observed at or near the contact of the dominantly arenaceous Wynd Formation and the argillaceous Old Fort Point Formation at two outcrops within the central zone of the anticlinorium (Plate V-7). They have been interpreted as exposures of zones of décollement between the two formations. These zones are believed to be only of a local nature as the Wynd-Old Fort Point contact has been observed at a number of localities to be devoid of such deformation.

A fold, unless it is perfectly similar, cannot continue upwards or downwards

indefinitely without changing its shape. Wynd strata, because of the large percentage of competent arenaceous beds, would tend to fold "more concentrically" than the underlying incompetent Old Fort Point. In the central zone, where the folding in both formations is close or tight, any zones of décollement or shearing off would be expected to occur at the contact of these two formations where there is a marked lithologic contrast. This shearing off and associated intense folding took place during the main folding phase (D_1) some time after the folds had begun to develop.

Reverse (Thrust) Faults

Reverse faults have been recognized at only four locations in the Meadow Creek Anticlinorium. Their influence on the structural fabric of the area is quite limited compared with that of the normal faults.

Description On Meadow Creek, at the westernmost outcrop of Member B of the Old Fort Point Formation, a low angle reverse fault displaces argillaceous siltstones (Figure 10). The fault dips 35° SW and strikes parallel to bedding which dips 45° SW overturned. In an outcrop 1500 feet to the northwest, the same fault is again exposed at the same stratigraphic level. The first few feet of the footwall adjacent to the fault have undergone minor drag folding at both localities. The fault zone is unveined and unbrecciated.

Along the Canadian National tracks about 2000 feet east of the Clairvaux Creek bridge, outcrops of Wynd arenite and slate expose a reverse fault. These outcrops are on the southwest limb of the anticlinorium which here dips southwest at about 40°. The footwall apparently is undeformed, but the hanging wall is folded into an

anticline whose axis strikes N 70° W and plunges 20° NW. Apparent dip of the fault in an east-west direction is about 25° to the west. The amount of displacement is unknown due to a lack of marker beds. Veining and brecciation are lacking, but the rocks immediately adjacent to the fault trace have undergone mild cataclasis (Plate X-5).

A high angle reverse fault of small extent and displacement is exposed in the folded belt of the southwest limb of the anticlinorium just north of the Miette River valley (Figure 10).

Normal Faults

Nine normal faults, confined to the central zone of the anticlinorium and intersecting both Wynd and Old Fort Point strata, have been mapped; some of these might be connected if outcrops were more extensive. One of the faults can be traced for a distance of 3 miles (Figure 10).

Occurrence and Attitude Normal faults have been recognized only on overturned northeast limbs of anticlines. They may also exist in the southwest limbs, but the paucity of outcrops hinders their recognition. The average strike of the faults is N 45° W, parallel to the strike of the axial surfaces of the central zone folds. Dips are to the southwest and, where actual measurements could be taken, values of 50°-60° were most common. The faults usually dip less steeply than bedding and cleavage; the average acute dihedral angle between the fault planes and bedding is 15°.

Deformation of Footwalls and Hanging Walls Aside from some brecciation, deformation in the footwalls and hanging walls caused by the faulting is negligible. Although two of the normal faults have footwalls that are intensely folded (Plate V-8), these folds are considered to have formed in the earlier episode of major folding, D_1.

Veining, Brecciation and Gouge Most of the normal faults have a prominent band of vein material associated with them. Commonly one can even find "float" of vein material at places where faults are expected but not exposed. The veins range in thickness from one to five feet. The dominant mineral is quartz (90-95 percent) with minor amounts of calcite, chlorite, siderite and albite. The veins often contain brecciated fragments of wall rock slate. Examination of thin sections of vein and gouge material from the faults shows that the quartz has more uniform extinction (less undulation) than quartz in the vein material from joints (Plates X-3 and X-4).

Gouge up to one and one-half feet thick is present along faults at a number of localities. It consists of a mixture of chlorite, muscovite, quartz, feldspar and siderite.

Kinematic Analysis of Faults

Normal Faults Slickensides may furnish some information regarding the direction and sense of movement along normal faults. The usefulness of slickensides is limited, however, because the direction and nature of displacement along a fault may vary with time and slickensides and associated "steps" may reflect only the last movements. Where slickensides were observed on the surfaces of normal

faults, only one trend was present. The pitch of the slickensides is about 90°, indicating that at these locations the net slip paralleled the dip-slip direction and the strike-slip was negligible. The average trend of the horizontal projections of the slickensides was about S 40° W, approximately normal to the trend of the central zone folds. Where asymmetrical steps occur on slickensided fault surfaces, the surface feels rough if the hand is moved up the fault surface on the footwall. In the past (Billings, 1954, p. 150), this has been interpreted to mean that the hanging wall has moved down relative to the footwall.

Outcrops adjacent to the faults also indicate that the hanging wall moved down relative to the footwall. Profile sections (Figure 22) indicate that dip-slip components of movement along the faults may range from less than 100 to more than 1000 feet. Using these values and an average dip for the faults of 55°, the throw on the faults ranges from 80 to 800 feet and the heave from 60 to 600 feet. Maximum values of stratigraphic throw may approach 1000 feet but estimates are difficult to make because of the lack of marker horizons in lower Wynd strata. The values given above naturally are subject to errors in the construction of the profile sections.

The amount and direction of net slip must, of necessity, vary along the length of the faults. Norris (1965), in his detailed study of normal faults in the Canmore area of Alberta, found an irregular variation in the net slip along strike. He observed that strike-slip components increased as one moved toward the extremities of the faults.

If one assumes that the depressed blocks of the normal faults are the active

ones, then they must increase in length as the displacement along the fault increases. This necessary elongation may have been realized by the opening up of OhO joints which trend perpendicular to the strike of the normal faults in the Meadow Creek Anticlinorium.

Reverse Faults There is little evidence available for a kinematic analysis of of the few reverse faults mapped in the area. Stratigraphic criteria and fault drag indicate that the hanging wall moved up relative to the footwall but there is no indication of the direction of the net slip.

Dynamic Analysis of Faults

Reverse (Thrust) Faults The reverse faults in the Meadow Creek Anticlinorium probably developed when the Old Fort Point and Wynd Formations were being folded. They developed at a greater depth and earlier than the normal faults of the area. During the folding the regional maximum principal stress trajectories probably plunged gently northeast (Charlesworth, 1959, p. 252). The minimum principal stress trajectories plunged steeply southwest. More locally, the attitude of the principal stresses would be controlled by the distribution of competent and incompetent strata. In the lower member of the Wynd Formation, the maximum principal stress trajectories were probably subparallel to the bedding in the competent arenaceous beds, dipping at a somewhat lower angle to the horizontal (see Bell and Currie, 1964, Fig. 5). The maximum shear trajectories are consequently inclined or subparallel to the bedding and thrusting would probably occur at low angles to the bedding. In the more homogeneous and incompetent Old Fort Point Formation, the "refraction" of the principal stresses toward the bedding would be less marked.

The reverse fault exposed along the Canadian National Railways tracks in the southwest limb of the Meadow Creek Anticlinorium may be similar, except in scale, to the "back-limb" thrusts that are found in the Foothills of the Canadian Rockies (see Irish, 1965, p. 105). These faults, which occur on the southwest limbs of anticlinal folds, are roughly curved and concave to the southwest. The reverse fault described by Griffiths (1962, p. 37) in the Wynd map-area also occurs on the "back-limb" of an anticlinal fold. The reverse faults in the Meadow Creek area probably die out in slate units.

The absence of brecciation along reverse faults is probably the result of the high normal stresses that existed across the fault planes.

Normal Faults The normal faults in the Meadow Creek Anticlinorium developed when the area was undergoing extension during epeirogenic uplift. When the faults formed the principal stresses were oriented in the following manner:

σ_1 acting approximately vertically

σ_2 acting from northwest to southeast and approximately horizontal

σ_3 acting from northeast to southwest and approximately horizontal

Many of the normal faults have narrow zones of brecciated rock and gouge associated with them. The normal stresses across the fault planes would have been less than the weight of the overburden. This would allow the strata in the vicinity of the fault zone to expand and brecciate.

The majority of normal faults in the Meadow Creek Anticlinorium dip 50° to 60° SW. The slaty cleavage is approximately parallel to or dips slightly steeper than

the faults. The cleavage and bedding was inclined to σ_1 at angles of about 30° when the faults were formed. Studies by Donath (1961) of experimentally produced shear failure in slates indicates that the presence of a well-developed cleavage has a marked effect on both the breaking strength of a rock and the angle of the shear fracture. In the experiments, shear fractures developed in or near the plane of cleavage for inclinations of 15° to 45° to σ_1. Specimens inclined at 30° had the lowest breaking strength. Increased confining pressure decreased the influence of the cleavage. In all except the 90° inclination, the "strike" of the shear fracture was parallel to that of the cleavage.

These experimental results indicate that the orientation of the cleavage in the Meadow Creek area favored the development of southwest dipping normal faults striking parallel to the cleavage.

Structure of the Old Fort Point Formation in Areas Other Than the Meadow Creek Anticlinorium

The writer has mapped the Old Fort Point Formation in the Portal Creek, Muhigan Creek and Yellowhead Lake Anticlinoria (Figure 1). These localities, along with the Meadow Creek Anticlinorium and the Jasper Anticlinorium (Evans, 1961) comprise the only known Old Fort Point exposures in the Jasper area. Details of the stratigraphy of these areas are to be found in Chapter 2.

Portal Creek Anticlinorium

This structure is located about 5 miles south of Jasper townsite. Most of the Old Fort Point outcrops are located east of the Banff-Jasper Highway (Figure 49). Exposures are of such poor quality and limited number that only the gross structural features can be recognized. The Old Fort Point Formation is exposed in an asymmetrical anticline whose axial surface strikes about N 50° W and dips steeply southwest. The northeast limb is overturned to vertical.

Muhigan Creek Anticlinorium

The Old Fort Point outcrops in the Muhigan Creek structure are situated about 4 miles west of Jasper townsite and 3 miles east of the Meadow Creek map-area (Figure 1). The outcrops occur in road cuts on the south side of the Yellowhead Pass Road (Highway 16); they range in quality from poor to excellent. Away from the road cuts themselves, outcrops are almost non-existent.

FIGURE 49

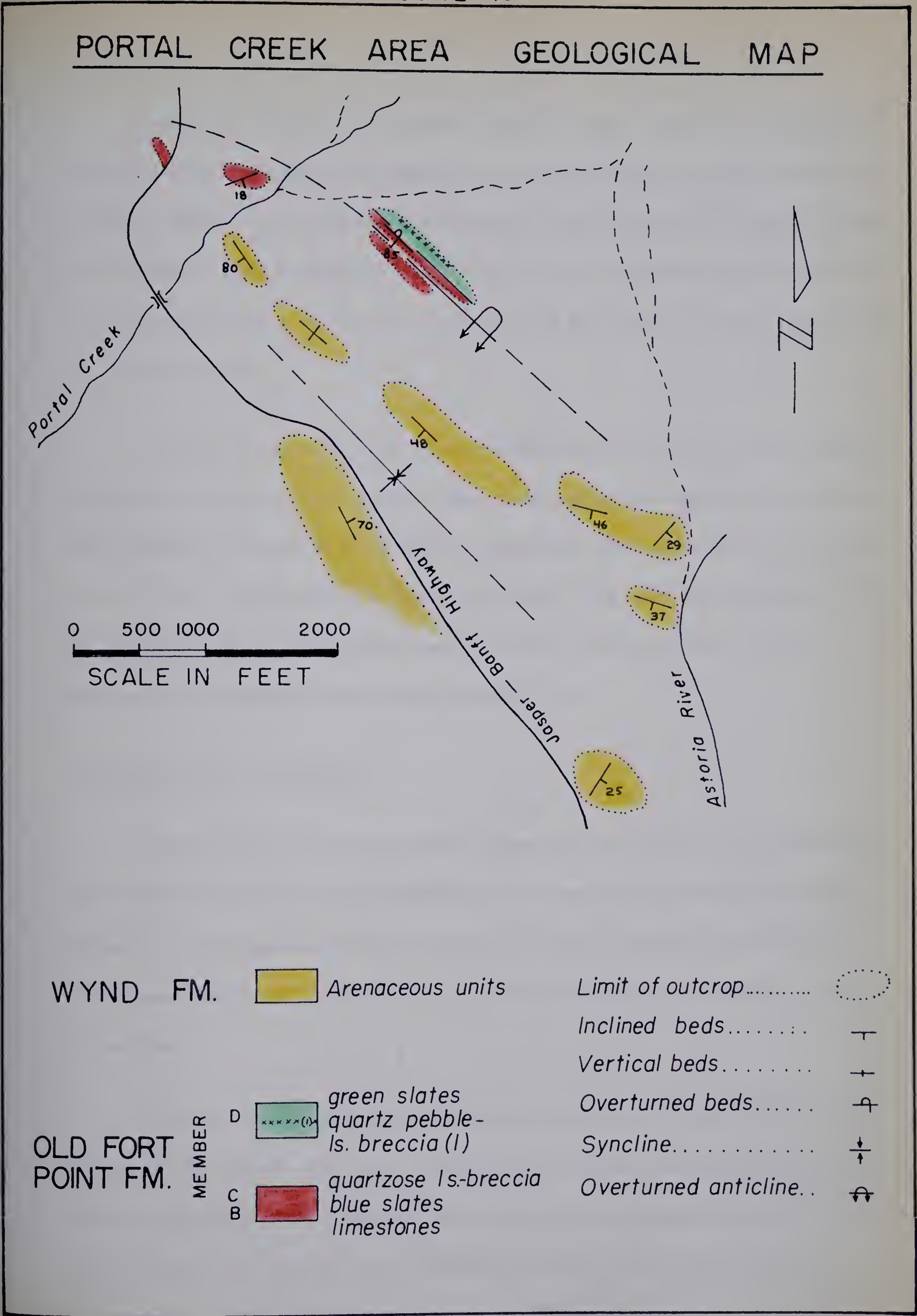

PORTAL CREEK AREA GEOLOGICAL MAP
Portal Creek
Jasper — Banff Highway
Astoria River
18
80
85
48
70
46
29
37
25
0 500 1000 2000
SCALE IN FEET
WYND FM.
Arenaceous units
OLD FORT POINT FM.
MEMBER
D
green slates
quartz pebble-
ls. breccia (l)
C
B
quartzose ls.-breccia
blue slates
limestones
Limit of outcrop
Inclined beds
Vertical beds
Overturned beds
Syncline
Overturned anticline

Figure 50 (in pocket) is a geologic map of the area. The structure of the Wynd strata to the northwest across the Miette River valley has been discussed by Bielenstein (1964). Adjacent to the highway, the structure is essentially that of a single asymmetrical anticline; Wynd strata dip 65° to 85° NE on the northeast limb and 30° to 50° SW on the southwest limb. The Old Fort Point strata on the northeast limb dip from 55° NE to 70° SW overturned.

In Figure 51, poles to S_1 for Wynd and Old Fort Point strata have been plotted. The scatter of points is considerable but the axis of folding (B_1) appears to trend about 120°, plunging northwest at a low angle. Bielenstein (1964) noted that S_1 - S_2 intersections in this area indicate a 10° northwest plunge. The axial surface strikes N 60°-85° W (Figure 34); on the northeast limb it dips at an average of about 35° SW, whereas on the southwest limb it dips at about 70° SW.

<u>Yellowhead Lake Anticlinorium</u>

Located about 18 miles due west of Jasper townsite (Figure 1), the Yellowhead Lake Anticlinorium contains the westernmost known occurrence of the Old Fort Point Formation. The exposures are found only on the hillsides immediately south of the Yellowhead Pass Road. Outcrops are poor and discontinuous and a theodolite was used to map them.

The structure here is an asymmetrical anticline overturned toward the northeast (Figure 53, in pocket). On aerial photographs, the anticline can be seen to extend 3 miles or more toward the southeast. Wynd strata in the northeast limb dip 50° to 65° SW overturned. The relatively incompetent Old Fort Point strata have been

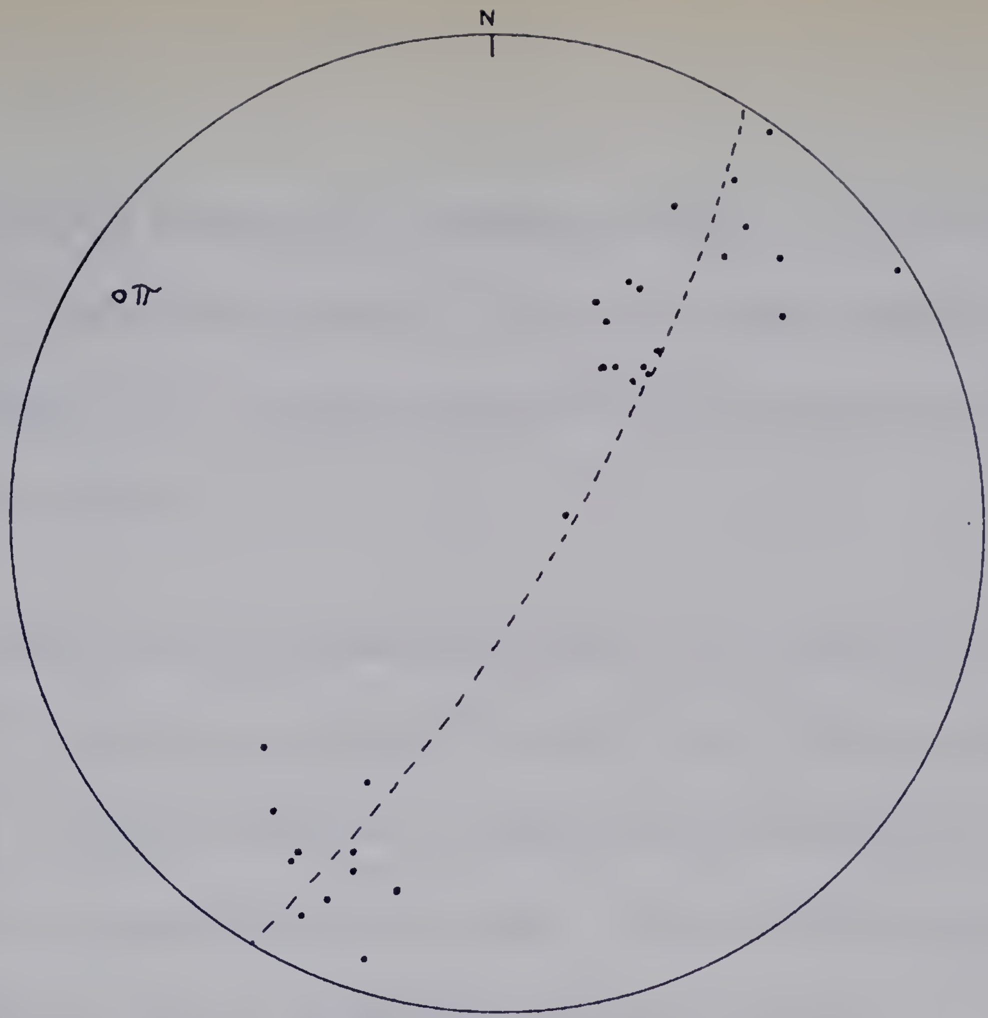


Figure 51 Equal-area diagram showing the orientation of poles to 30 S_1 planes in the Old Fort Point Formation and the Wynd Formation in the Muhigan Creek Anticlinorium.

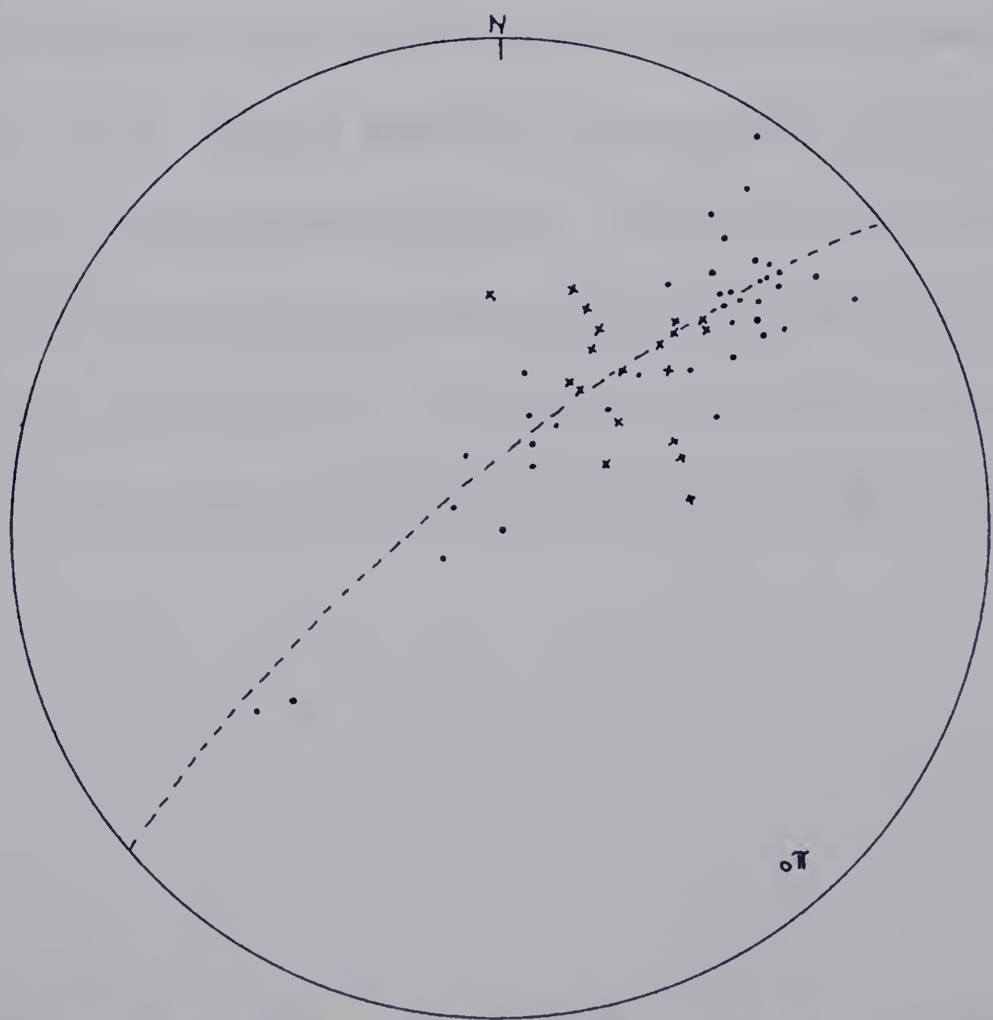


Figure 52 Equal-area diagram showing the orientation of poles to 39 S_1 planes (·) and 18 S_2 planes (×) in the Old Fort Point and Wynd Formations of the Yellowhead Lake Anticlinorium.

deformed into at least two asymmetrical, overturned anticlines. Axial surfaces of the folds strike N 60° W and dip 30° to 50° SW. The axis of folding trends about 140°, plunging 10° SE (Figure 52). Traverses on the north side of the lake failed to reveal any Old Fort Point outcrops.

Slaty cleavage is well-developed in the Old Fort Point Formation; dips range from 20° to 50° SW. One fault, possibly of the normal type, was recognized in the northeast limb. It is marked by thick veins of quartz and brecciated slate. Kink folds (F_2) were seen in a small number of slate outcrops. They are similar in orientation and sense of movement to those in the Meadow Creek Anticlinorium.

Conclusions

Throughout the Jasper area, the Old Fort Point Formation has been deformed in essentially the same manner. Folds in different anticlinoria differ little in their geometry, gross orientation, style, symmetry and size. The only variation which may be of regional significance is the progressive decrease in dip of the axial surfaces of folds as one proceeds farther west (Figure 54). In the Jasper Anticlinorium, they dip 65° to 75° SW, whereas in the Yellowhead Lake Anticlinorium, they dip from 30° to 50° SW.

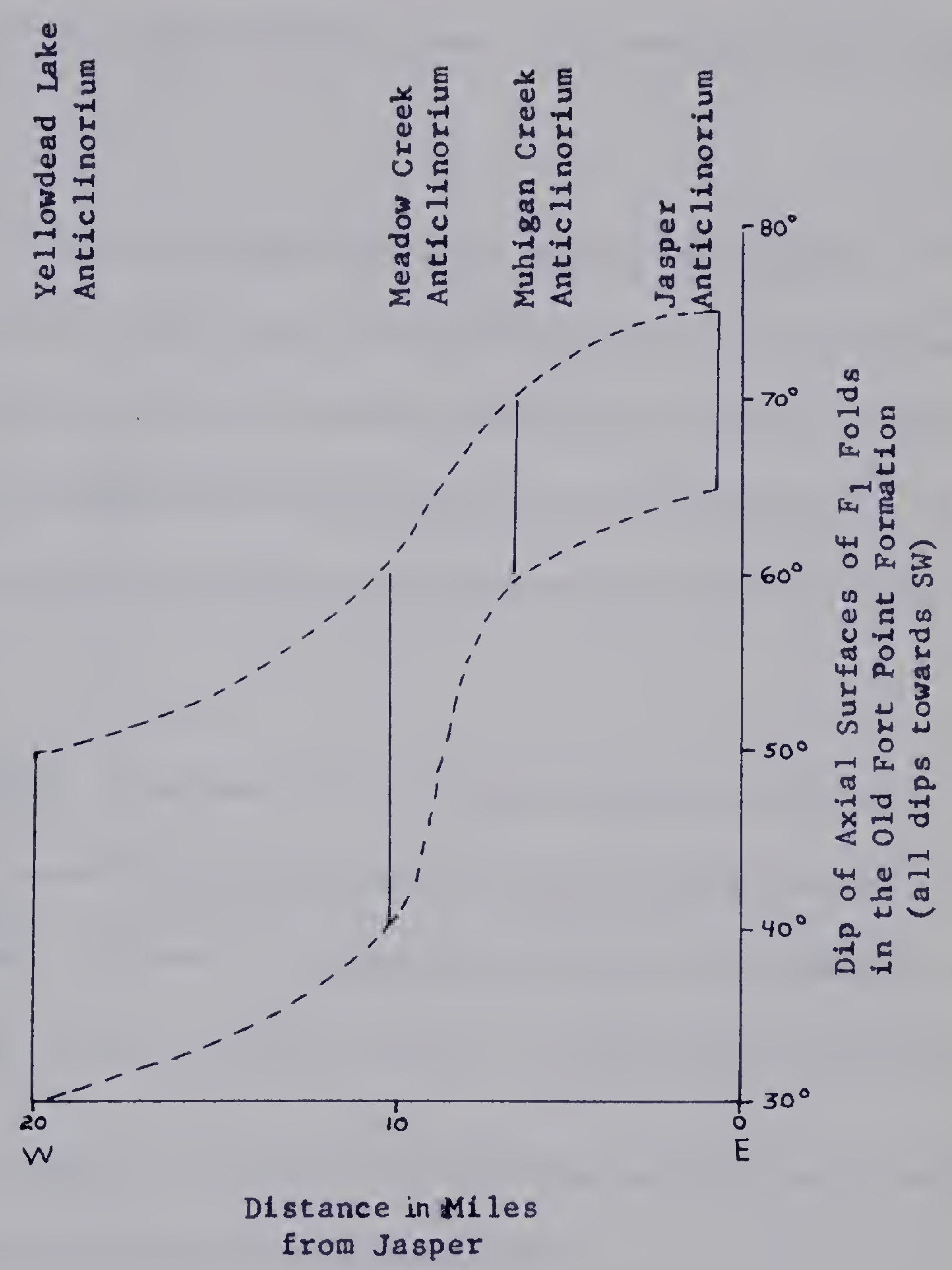


Figure 54 Progressive decrease in dip of axial surfaces of F_1 folds with increasing distance westward from Jasper.

Sequence of Tectonic Events in the Meadow Creek Anticlinorium

The following is the probably sequence of tectonic events that took place in the Meadow Creek Anticlinorium and nearby areas. The events are listed in chronological order.

(1) Major folding and associated low-grade regional metamorphism The F_1 folds in the Meadow Creek Anticlinorium developed during a phase of the widespread thrusting and folding involved in the formation of the Canadian Rocky Mountains. This major event may have occurred as late as Late Eocene or Early Oligocene times (Shaw, 1963). Slaty and fracture cleavage development and minor thrusting occurred during the folding.

(2) Kink folding Sometime after the F_1 folds had ceased to develop a compressive stress field caused kink folding to occur by laminar gliding along previously formed cleavage planes. Whether this compression was related to the stress field that caused the F_1 folds to develop or whether it records a separate event is not known.

(3) Normal faulting The normal faults were the last structures to form and resulted from the extension caused by epeirogenic uplift.

CHAPTER 4 - METAMORPHISM, VEINING AND IGNEOUS ROCKS

The Proterozoic sediments of the Jasper area have been subjected to low-grade regional metamorphism that was both thermal and dynamic in nature. The grade of metamorphism may be classified as belonging to the quartz-albite-muscovite-chlorite subfacies of the greenschist facies (Turner and Verhoogen, 1960). To the west of the area, the grade of metamorphism increases. Radiometric dating of the metamorphic rocks indicates that metamorphism occurred sometime later than 70 million years ago.

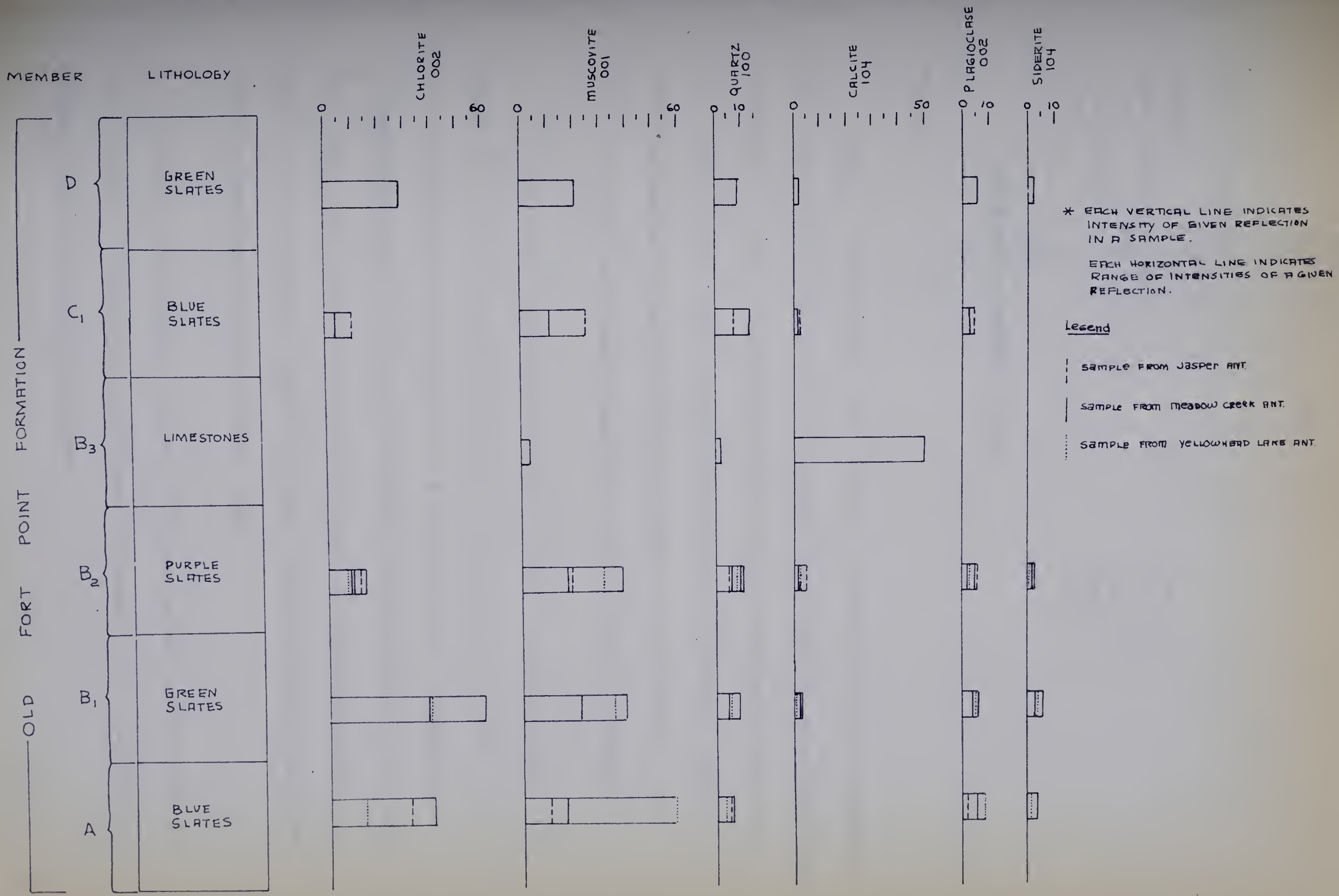
Mineralization has occurred along many of the joints and normal faults. A lone outcrop of a highly altered igneous intrusive has been discovered in the Jasper area. It was intruded sometime before the area was deformed and metamorphosed.

Mineralogy of the Metamorphic Rocks and Vein Fillings

Methods of Study

The fine-grained nature of most of the Old Fort Point Formation lends itself to study by X-ray diffraction techniques. The various minerals present can be identified, and changes in the relative proportions of minerals sometimes can be observed. A Norelco high angle Geiger-counter diffractometer with Cu tube and Ni filter was used. Samples were ground in a Bleuler grinder for 1 minute and then either made into pressed biscuits or poured loose into an aluminum sample holder. The pressed biscuit method of sample preparation imparts a high degree of preferred orientation to the platy minerals such as chlorite and muscovite. Basal spacings can be measured quite

Figure 55 Intensity of X-ray Reflections for Major Minerals in Samples from the Old Fort Point Formation *



readily with such biscuits. The loose powder mounts are necessary if one is to obtain non-basal reflections from platy minerals. For routine identification of minerals, the following instrumental settings were used: goniometer speed, 1° 2θ per minute, chart speed, 1/2 inch per minute; divergent, scatter, and receiving slits, 1,1, and .003 inches, respectively; and scale factor, multiplier, and time constant, 8, 1, 4, or 4, 1, 4 respectively. For careful measurements of peak positions, goniometer speeds of $1/4^\circ$ or $1/8^\circ$ per minute were used. Quartz was used as an interval standard.

Uncovered thin sections and polished rock specimens were etched with hydrofluoric acid fumes and stained with sodium cobaltinitrite and rhodizonate solution to aid in the identification of feldspars. The thin sections gave consistently good results whereas the polished rock specimens yielded poorer results. About 110 thin sections were measured.

Mineral Assemblages

The assemblages of minerals present in the rocks and vein fillings of the Old Fort Point Formation are listed in Table 12. The more abundant minerals are starred. In Figure 55, the results of the X-ray diffraction survey of samples from the Old Fort Point Formation are plotted.

TABLE 12: Mineral Assemblages in the Old Fort Point Formation of the Jasper Area

Rocks	Joint Vein Fillings
Chlorite*	Quartz*
Muscovite*	Calcite*
Quartz*	Siderite
Albite*	Chlorite
Calcite*	
Siderite	Normal Fault Veins

Figure 55 Intensity of X-ray Reflections for Major Minerals in Samples from the Old Fort Point Formation *

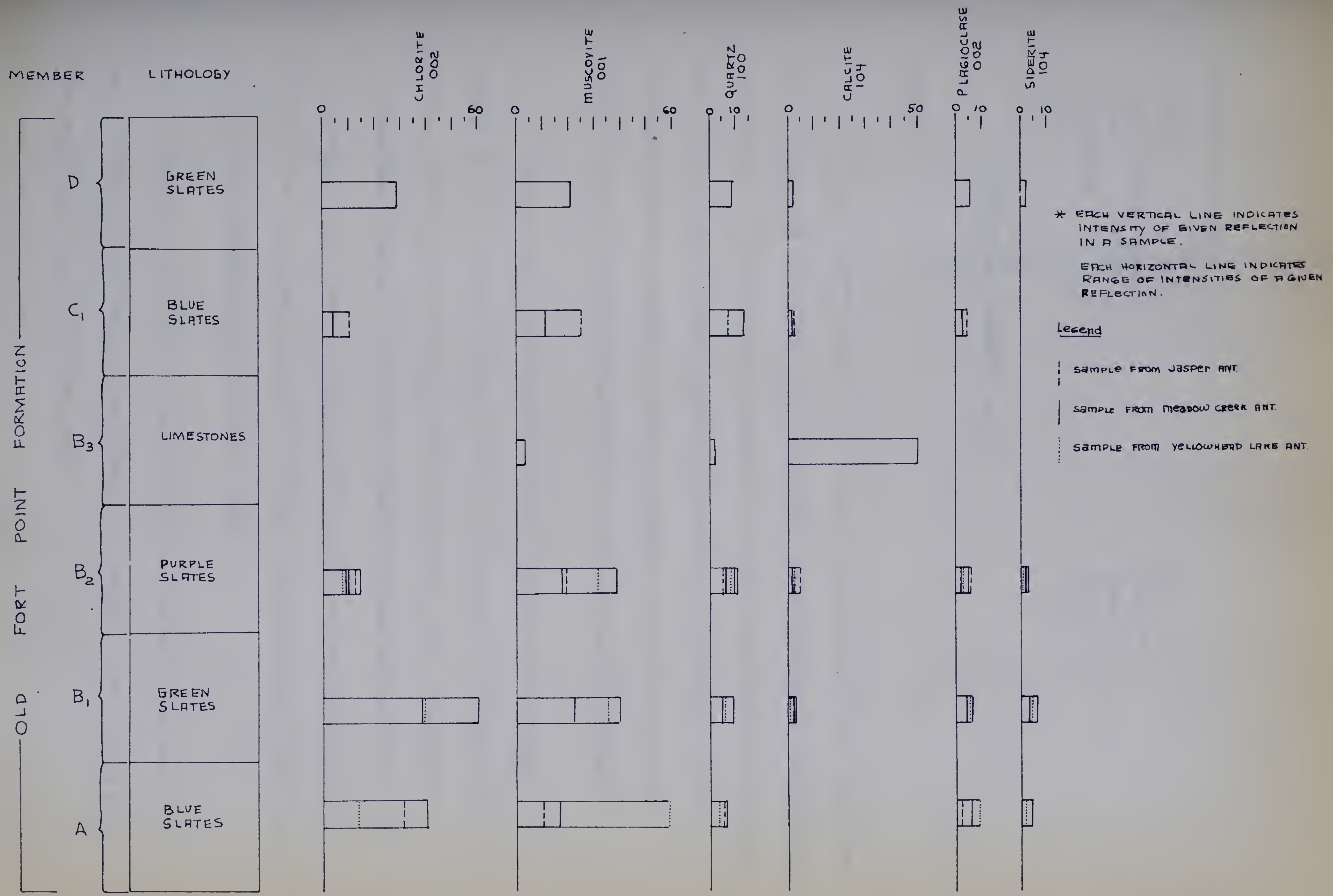


Table 12 continued:

Biotite	Quartz*
Heavy accessory minerals	Calcite*
Zircon	Chlorite*
Tourmaline	Siderite
Rutile	Albite

* Indicates more abundant minerals.

<u>Minerals</u>

<u>Chlorite</u> Chlorite has been found in every sample from the Old Fort Point Formation. It occurs as minute flakes and as ellipsoidal-shaped books, sometimes interleaved with muscovite. The books usually have their long axes oriented parallel to the cleavage. Chlorite is also a common constituent of normal fault vein fillings. Stauffer (1961) has reported its presence in joint vein fillings in the Wynd Formation. The chlorite is optically negative and is pale green in color and usually pleochroic.

In every sample, sharp $7A^o$ and weaker $14A^o$ chlorite peaks are present. This suggests, but does not prove, that most if not all of the chlorite is "normal" $14A^o$ chlorite and not septechlorite (chlorite with a $7A^o$ basal spacing). Septechlorites are lower temperature polymorphs of $14A^o$ chlorites (Warshaw and Roy, 1961). Some of the original clay minerals in the Old Fort Point may have been septechlorites that have since been converted to normal $14A^o$ chlorite. Septechlorites have been identified in unmetamorphosed sediments (Pelzer, 1965).

Kaolinite, which might be obscured in the X-ray pattern by the presence of the $7A^o(002)$ peak of chlorite, is not believed to be present. Slow scanning of the 7Ao peak failed to resolve it into two peaks.

An attempt was made to determine the composition of the chlorite using the method outlined in Brindley (1961). Eight samples of slate, one sample of fault vein chlorite, and a sample from the igneous intrusive on Yellowhead Road were utilized. The mean cell dimensions derived from the slates were d(001) equals 14.377A° and d(060) equals 1.543A°. Using the graphs in Brindley, the average composition of the chlorites in slates was calculated as $(Mg)_{4.07}(Fe, Al)_{0.63}(Al_{0.63}Si_{3.37})O_{10}(OH)_8$. The ratio of Mg^{++} to Fe^{++} ratios are 3.1 to 1 and 1.7 to 1, respectively. Evans (1961) and Stauffer (1961) reported comparable ratios of 3.67 to 1 and 3.6 to 1, respectively. This data indicates that the chlorites of the Old Fort Point Formation are relatively rich in iron.

Muscovite This mineral is perhaps the most abundant one in the Old Fort Point Formation. It is present largely as minute flakes oriented parallel to the cleavage, but occasionally is interleaved with chlorite in ellipsoidal books. The muscovite flakes in the Jasper area (Plate VII-1) slates lack the well crystallized outlines of the muscovite in the phyllites from the higher grade rocks of the Mount Robson district (Plate VII-8). Muscovite is not found in vein fillings and is also absent in the igneous intrusive.

The dioctahedral muscovite is easily recognized in X-ray diffraction patterns by the presence of the strong 001 peak at about 8.8° 2θ. In all samples the shape of the peak was found to be very sharp. The average 001 d spacing for eight samples of slates is 9.9945A°.

Using the data of Yoder and Eugster (1955), an attempt was made to identify the polymorph of muscovite present in the slates. The eight samples used were slates chosen for potassium-argon age dating. The results are listed in Table 13. They

TABLE 13: X-ray Determination of Muscovite Polymorph

2M 2θ values*	3T 2θ values*	AK 370	AK 371	AK 372	AK 373	AK 374	AK 375	AK 376	AK 377
		sample 2θ values							
8.83	8.87	8.83	8.80	8.85	8.85	8.85	8.87	8.81	8.87
17.66	17.77	17.78	17.73	17.80	17.78	17.78	17.78	17.75	17.79
19.82	19.76								
19.91	19.90	19.90	19.90	19.80		19.95	19.90	19.88	19.90
22.86	22.96	22.85	22.80	22.80		22.90	22.90	23.00	22.90
23.82	24.75	23.80	23.80			23.80	23.90	23.90	23.90
25.45		25.25	25.22	25.25	25.25	25.27	25.22	25.23	25.27
26.60	26.75	26.80	26.75	26.72	26.80	26.80	26.80	26.78	26.80
27.81		27.80	27.90	27.95	28.00	28.00	27.90	27.78	27.90
29.80		29.83	29.90	29.90	29.90	29.98	29.90	29.90	29.90
31.16		31.20	31.20	31.20	31.20	31.30	31.22	31.30	31.30
31.93		31.90	32.00	31.70	31.70	31.85	31.70	31.70	31.70
35.03	35.00	35.00	35.00	35.02	35.05	35.00	35.00	35.00	35.05
	35.94	35.99	35.92	35.99	35.95	35.95	36.00	35.95	36.00
36.55	36.56	36.53		36.59	36.50	36.60	36.50	36.60	36.50
37.79	37.73	37.70		37.80			37.90	37.80	37.78
40.12									
40.34				40.30					
41.00		41.00		41.20					41.00
42.05		42.00	42.10	42.00		42.00	42.10	42.00	
42.39	42.31	42.40	42.40	42.45	42.50	42.55	42.50	42.40	42.50

* 2M and 3T 2θ values are from Yoder and Eugster (1955)

indicate that the polymorph present is probably the 2M (two-layer monoclinic) variety.

Albite The composition of the feldspars in the Old Fort Point and Meadow Creek Formations was determined by staining techniques, extinction-angle measurements of polysynthetically twinned grains, and refractive index measurements. The results indicate that the composition of the plagioclase is in the range An_0 to An_{10}. Potash feldspar does not appear to be present in these two formations.

Albite is almost ubiquitous and is present as detrital grains and pebbles. It is found in every lithology-slate, siltstone, sandstone and limestone. Authigenic overgrowths of albite on detrital albite grains have been recognized. Albite is also found is some of the joint fillings as small twinned crystals.

The 002 albite peak at about 27.9°2θ was used for the recognition of albite in X-ray diffraction samples. This peak is present in virtually every sample (Figure 55).

The weight percent of Or in the albite can be estimated by measuring the angular separation of ($\bar{2}01$) albite and (101) for K_2BrO_3 which is added as an internal standard (Orville, 1958). Because the percentage of albite in the slates is so small, a sample of the Yellowhead Road igneous intrusive was used. The albite in this rock showed an angular separation of 1.87° 2θ indicating that the weight percent of Or is insignificant.

Attempts were also made to determine whether the plagioclase was of the low or high temperature variety (Smith and Yoder, 1956, p. 641). Results were inconclusive because the $1\bar{3}1$ and 131 peaks could not be satisfactorily resolved. Stauffer (1961)

reported that samples of plagioclase from the lower Wynd Formation were found to be of the low temperature variety.

In the lower Wynd Formation, potash feldspar appears to be nonexistent (Griffiths, 1961; and Bielenstein, 1964). In the upper Wynd, both potash and plagioclase feldspar are found (Bielenstein, 1964), whereas in the overlying Jasper Formation, potash feldspar is common and plagioclase feldspar virtually absent (Akehurst, 1964).

Quartz Quartz has a widespread distribution throughout the Old Fort Point Formation. It is present in sizes ranging from silt grains to large pebbles. It is also commonly found as the major constituent of vein fillings along joints and faults.

Quartz grains in the sediments show little evidence of recrystallization during metamorphism. Some of the sand-sized grains have overgrowths (Plate VII-5) but these are indicative of a previous sedimentary cycle. Quartz grains sometimes show replacement along their margins by calcite. The larger quartz grains and pebbles usually exhibit undulatory extinction inherited from the source terrain.

Although quartz grains may have their longest dimension oriented parallel to the cleavage, there is little indication that the grains have actually been elongated while the rocks were being metamorphosed. In arenaceous limestone breccias (Plate IX-4 and II-7) where the limestone phenoclasts have been severely deformed, the quartz sand grains do not show a pronounced elongation.

Quartz in vein fillings of joints and faults occurs in masses up to 5 feet thick.

Veins in quartzose rocks are more apt to be made up largely of quartz than veins in rocks rich in calcite. Joint vein quartz is characterized by extremely wavy extinction (Plate X-3), whereas fault vein quartz has more clear cut extinction, (Plate X-4).

Quartz is easily recognized in X-ray diffraction patterns. The 100 reflection is used as an internal standard for careful measurement of 2θ values.

Calcite During metamorphism calcite was largely stable. It is present in almost every sample of the Old Fort Point Formation sediments. It is also a common constituent of fault and joint vein fillings.

Calcite of sedimentary origin is principally present as anhedral untwinned microcrystalline grains, either in bedded limestones or scattered throughout slates and siltstones. In the highly deformed limestone phenoclasts in Plates IX-6, II-7 and II-8, the calcite grains are elongated parallel to the "a" fabric axis. Calcite can be seen to replace quartz and plagioclase grains in sandstones and siltstones (Plate VII-5). Some of the calcite in the sediments has recrystallized to form larger, often twinned grains. In limestone-breccias, the calcite at the margins of the phenoclasts and in the matrix is often much coarser grained.

Calcite in vein fillings is coarser grained and occurs in pods up to 3 inches in length. Veins in rocks high in calcite usually contain more calcite than quartz. Joint vein calcite (Plate X-2) is usually twinned, some of the lamellae being bent and kinked. Fault vein calcite is usually untwinned.

The principal peak of calcite, the 104 peak, is easily recognized in X-ray

diffraction patterns. Five samples representing the range of occurrences of calcite were studied to find the mole percent of $MgCO_3$ in $CaCO_3$. Curves in Goldsmith and Graf (1958, p. 97) were utilized. The results are shown in Table 14. The calcite is of the low magnesian variety.

Dolomite does not appear to be present in the Old Fort Point Formation. Staining tests and X-ray diffraction patterns gave negative results. Dolomites form an important part of the upper part of the Miette Group near Yellowhead Lake (Mountjoy, 1962).

TABLE 14: Determination of Mole Percent of $MgCO_3$ in $CaCO_3$

Sample Description	dÅ(104)	Mole percent $MgCO_3$ in $CaCO_3$
Bedded limestone, Member B_3, Meadow Creek	3.0414	0
Bedded limestone, "Miette Group", Mount Robson area	3.0273	3.5
Slate, Member B_2, Meadow Creek	3.0374	0
Joint vein calcite, Meadow Creek	3.0293	2.0
Normal fault vein calcite, Meadow Creek	3.0425	0

Siderite This mineral is present in small amounts in most samples. It is most abundant in the Yellowhead Lake area. In the sedimentary rocks, it occurs as small anhedral grains or as rhombs up to 2 mm in size (Plates X-6 and VI-1). In places siderite can be seen to replace calcite. The rhombs often contain silt-sized grains of quartz and/or feldspar. Alteration of siderite to hydrous iron oxide is quite common

and accounts for the prominent rusty appearance of the siderite in hand specimens. The distribution of siderite in a sample appears to have no relation to the sedimentary stratification within the rock. Slaty cleavage is always wrapped around the siderite grains of sediments and thus indicates that they are pre-metamorphic in origin.

Siderite also is common in vein fillings along normal faults. It occurs as crystals up to 5 mm in size and is usually strongly altered.

Krumbein and Garrels (1952) have shown that siderite formation requires an absence of oxygen. It can form at pH above or below 7.8 (limestone fence). Because the siderite is present in shallow marine and perhaps even nonmarine sediments, it either records a micro-reducing environment or is secondary in origin. Its distribution in the sediments suggests that the latter case is more likely. It may have formed by the replacement of calcite by iron bearing solutions.

Siderite is identified in X-ray diffraction patterns by its principal peak 104 at a 2θ value of about 31.9°.

<u>Biotite</u> Pale brown pleochroic flakes of biotite, up to 0.03 mm in length, are found in the Member A siltstone beds from the Meadow Creek and Jasper areas. The biotite flakes have ill-defined outlines and appear to be altering to chlorite in some instances.

Biotite is an important constituent of the pelites and psammites of the Mount Robson area. A separate of biotite from this area was dated by the potassium-argon method.

Regional Variations in Grade of Metamorphism

Lateral Variations

Figure 56 shows the distribution of important metamorphic minerals and rock types in the Main Ranges and Western Cordillera to the west of Jasper. The grade of metamorphism increases westward from Jasper towards the Rocky Mountain Trench. In the Front Ranges to the east of Jasper the rocks are not visibly metamorphosed.

All the known exposures of the Old Fort Point Formation lie within a 20-mile wide belt in which the grade of metamorphism corresponds to the quartz-albite-muscovite-chlorite subfacies of the greenschist facies (Turner and Verhoogen, 1960). The above assemblage of minerals, along with calcite and siderite, are ubiquitous throughout the Old Fort Point. Biotite, an important metamorphic mineral farther west, is present only as occasional detrital flakes in part altered to chlorite and muscovite. Systematic east-west variation in the composition of the Old Fort Point minerals has not been observed, but potassium-argon dates (Chapter 5) show a gradual decrease from east to west and may be considered as an index of incresing metamorphism in this belt of uniform mineralogy.

The boundary between the chlorite and biotite isograd as drawn in Figure 56, was not located in the field by this writer. Undoubtedly it consists of a transitional zone. A small number of samples of Miette Group psammites and pelites were collected near Mount Robson Station. They consist largely of biotite, muscovite, quartz and feldspar. Chlorite is not present. The biotite and muscovite flakes have well-crystallized outlines compared to the muscovite flakes in the Old Fort Point Formation

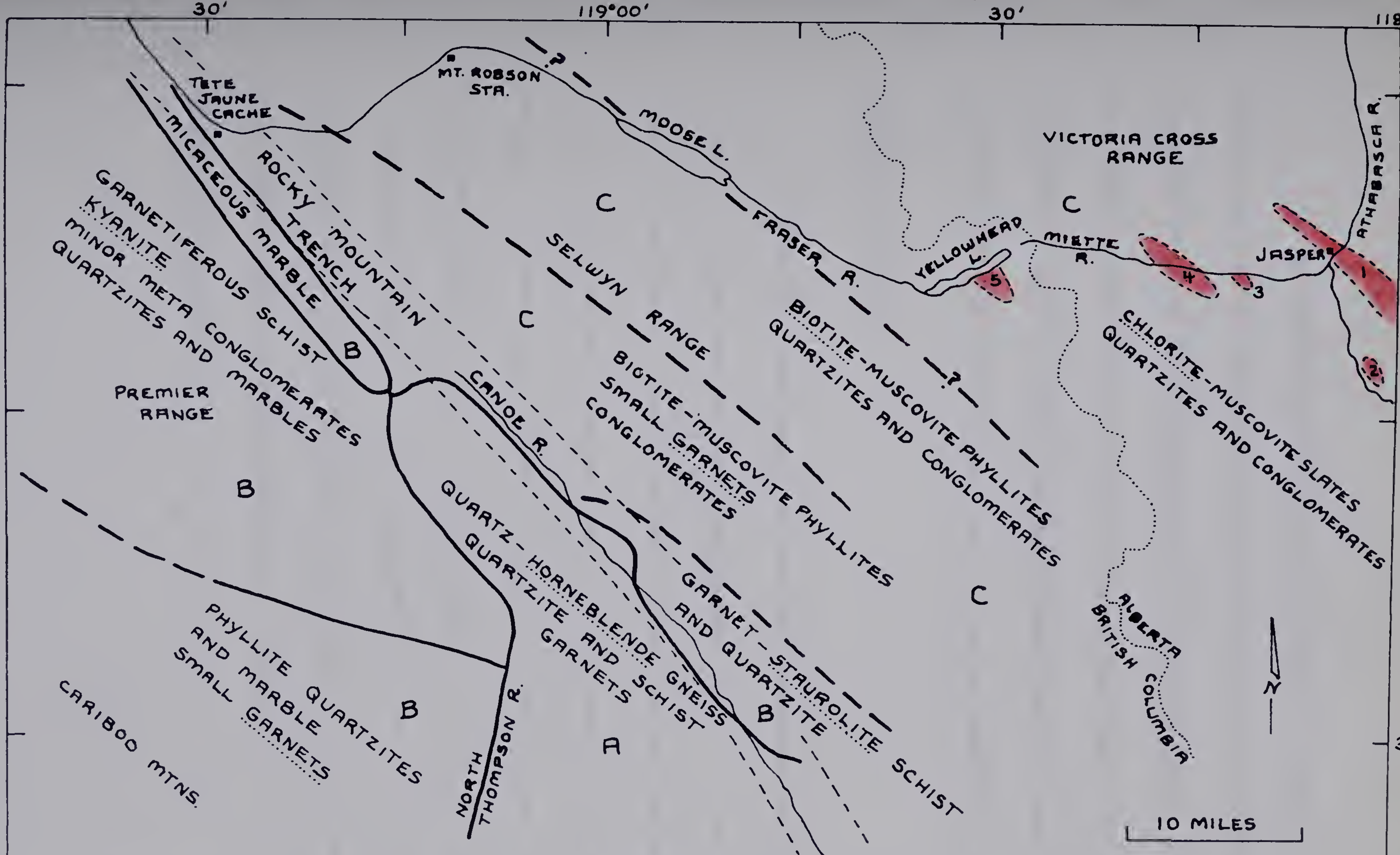


FIGURE 56

DISTRIBUTION OF MAJOR METAMORPHIC MINERALS AND ROCK TYPES IN MAIN RANGES AND WESTERN CORDILLERA WEST OF JASPER

MAINLY MODIFIED FROM CAMPBELL (1965)

PROTEROZOIC AND CAMBRIAN?

- C MIETTE GROUP
- B KAZA GROUP
- A SHUSWAP METAMORPHIC COMPLEX

LOCATIONS OF OLD FORT POINT FM.

1 JASPER ANT.
2 PORTAL CREEK ANT.
3 MUHIGAN CREEK ANT.
4 MEADOW CREEK ANT.
5 YELLOWHEAD LAKE ANT.

farther east.

On the western slopes of the Selwyn Range, located about 30 miles across the stike of the Main Ranges from Jasper, small garnets are present in the biotite-muscovite phyllites of the Miette Group (Campbell, 1965). Across the Rocky Mountain Trench in the Western Cordillera even higher grade rocks are present - gneisses and schists. Campbell (ibid.) believes these higher grade rocks are stratigraphic equivalents of the Miette Group strata on the east side of the Trench.

Vertical Variations

Within the Jasper area, the low-grade metamorphism appears to decrease in intensity in higher structural and stratigraphic levels. In the Meadow Creek, Old Fort Point and lower Wynd Formations, albite is the only stable feldspar. In the upper Wynd, potash and soda feldspars coexist. In the overlying Jasper Formation, potash feldspar is common; soda feldspar is missing but probably was absent from the original sediments (Akehurst, 1964). Akehurst (ibid., p. 19) states "Metamorphism of the rocks in the Jasper Formation is either nonexistent or of very low grade". Examination by the present writer of thin sections of argillaceous rocks from the Jasper Formation fails to show evidence of slaty cleavage. Veining is also an uncommon phenomenon in the Jasper arenites.

Metamorphism of the Old Fort Point Formation in the Jasper Area

Possible Pressures and Temperatures Prevailing During Metamorphism

Fyfe, Turner and Verhoogen (1958) consider that the minerals of the green-schist assemblage probably develop at temperatures of 300° C and more under load pressures of about 3000 bars. Water pressure (P_{H_2O}) is equated to load pressure. They base their interpretation on experimental data and on the geolocial observations of workers such as Coombs (1954).

A survey of published stratigraphic sections in the Jasper and surrounding areas indicates that the Old Fort Point strata may have been buried beneath a minimum of 25,000 to 35,000 feet of sediments (8 to 11 km) when they were metamorphosed. This thickness of sediments would account for a load pressure of 3000 to 4000 bars. To this pressure would have to be added the pressure resulting from tectonic stresses in existence when the rocks were being folded and metamorphosed. To obtain a temperature of about 300°C at a depth of 8 to 11 km a linear geothermal gradient of 27° to 38°C/km would be required. Wyllie and Tuttle (1960) concluded that a value of 30°C/km is reasonable for geothermal gradients in geosynclines.

Behavior of Minerals During Metamorphism

Before regional metamorphism took place, the argillaceous strata of the Old Fort Point Formation probably consisted largely of illite and chlorite. Illite is the most abundant clay mineral in shales. The illite provided the basic materials for the principal low-grade metamorphic reactions.

Studies of illite-chlorite relationships at low temperatures (Velde, 1964) has provided important facts concerning the development of the greenschist mineral assemblages. Velde found that when natural illites are heated to temperatures of about 300°C an "unmixing" of mixed layer illite occurs and a mica and chlorite and quartz assemblage is formed. This is the same assemblage that marks the appearance of the greenschist facies. The 300°C temperature required for the reaction lends support to Fyfe, Turner and Verhoogen's conclusion that the greenschist facies minerals form at temperatures of 300°C and higher. The illites used had a bulk composition of about 6 percent potassium. Experiments conducted with a higher percentage of potassium in the system inhibited the "unmixing" of the illite and chlorite was not formed. The average K_2O value for 13 Old Fort Point and Wynd slates is 4.6 percent (Chapter 5, Table G-1). Therefore, the potassium content of the original shales was low enough to allow the formation of mica (muscovite) and chlorite during metamorphism.

The previously described reaction suggests that some of the chlorite in the Old Fort Point is of metamorphic origin. The remainder of the chlorite was originally present in the shales and was stable during metamorphism. Most of the ellipsoidal chlorite books are premetamorphic in origin and behaved as clastic grains which were mechanically rotated into the cleavage plane. Expansion of large numbers of books parallel to the "c" axis prior to metamorphism may explain why most of the books oriented in the cleavage have their "c" axes and longest dimension parallel (Evans, 1961). The expansion may have taken place when biotite flakes were altered to chlorite. In the Mount Robson area, the chlorite was removed by the reactions that formed the biotite.

Albite was stable under the existing conditions of temperature and pressure during metamorphism. Original grains and pebbles of albite composition remained unchanged. Calcic and potash feldspars, on the other hand, were unstable and were broken down to form albite, calcite and muscovite.

Quartz was stable during metamorphism. Some of the quartz in the pelites was produced by the unmixing of illite but this fraction was not identified under the microscope. Calcite was also largely stable, although some recrystallization to form larger grains did occur, especially at the margins of limestone phenoclasts and in the matrix of limestone breccias. The calcite elongated parallel to the "a" fabric axis in the highly deformed limestone phenoclasts (Plates II-7 and IX-8) may be a product of strain without accompanying syntectonic recrystallization. The feldspars in the igneous intrusive described below are highly altered to calcite, yet the original calcite in nearby limestone beds appears to have been stable. This indicates that the partial pressure of CO_2 in the pore fluids must have been fairly high (Fyfe, et. al, 1958). Siderite was also stable during metamorphism.

Brief Summary of Conclusions Regarding Metamorphism

The Old Fort Point Formation was probably metamorphosed at depths of 8 Km. or more at temperatures of about 300°C. The main metamorphic reaction was the conversion of unstable illite to muscovite, chlorite and quartz. A quantitatively less important reaction was the breakdown of calcic and potassic feldspars to form albite, muscovite and calcite. The chlorite, quartz, siderite and calcite present in the original unmetamorphosed sediments were largely stable but underwent mechanical reorientation and sometimes strain during the formation of slaty cleavage.

Veining

The veining of joints and fault zones took place at shallower depths than the metamorphism. The very presence of quartz, calcite, siderite, chlorite and albite in the veins indicates that they were stable under the prevailing pressure and temperature conditions. As has been previously stated, the mineralogy of the wall rock may have influenced the mineralogy of the vein filling. Calcareous rocks have veins richer in calcite than more siliceous rocks. The difference in the extinction of the quartz and the deformation of calcite grains in joints and normal fault veins suggests that there were at least two periods of veining; joint veins being emplaced earlier and experiencing mild deformation, and fault veins being emplaced later and not showing evidence of deformation.

Intrusive Igneous Rocks

The only known occurrence of an igneous intrusive rock has been located by the writer in a small outcrop within the Meadow Creek Anticlinorium (Figure 10, Plate I-7 and 8). Intruded with slight angular discordance into Member B_3, Old Fort Point Formation, it is about 10 feet thick. The rock is green, fine grained, and shot through with white flakes. Small pyrite cubes up to one-half inch in size are scattered throughout the rock. The intrusive is penetrated by a pronounced cleavage and is extensively fractured and veined with quartz, calcite and siderite. The limestones, although they appear unaltered in thin section, have a baked appearance in the outcrop. Slates up to 2 feet away from the contact have been changed from purple to green in color.

Photomicrographs of thin sections of the intrusive are shown in Plate X-7 and 8. Samples from the middle of the instrusive consist of about 40 percent plagioclase, 20 percent calcite, 20 percent chlorite, and 10 percent leucoxene. The remainder is siderite and pyrite. The plagioclase occurs as laths (Plate X-8) up to 1 mm in length and extinction angle measurements indicate an albite or oligoclase composition. Plagioclase is extensively altered to calcite. Samples from the margins of the intrusive are finer grained. The intrusive may have originally been a diabase.

The deformation and metamorphism experienced by the intrusion indicates that it was intruded prior to the main episode of folding and metamorphism. The nearest known igneous rocks in the Rocky Mountains are the Crowfoot dike of unknown age (Smith, 1963), the Devonian Ice River Complex (Baadsgaard _et al_., 1961), and the Cross River intrusives of unknown age (Hedley, 1954).

CHAPTER 5 - GEOCHRONOLOGY

Introduction

The potassium-argon method of radiometric dating was applied to whole-rock samples and mica separates from the Jasper and Mount Robson areas. The aims of this investigation were: (1) to determine the age of the source terrain of the sediments, (2) to ascertain the time or times that the rocks were metamorphosed and (3) to add to our understanding of the problems encountered in dating sedimentary rocks that have been exposed to low-grade thermal and dynamic metamorphism.

Stauffer (1961), Evans (1961) and Steiner (1962) have dated samples from the Precambrian of the Jasper area. Results of their determinations are listed in Table 15. Their conclusions are discussed later.

Materials and Methods Employed

Collection of Samples

Nine oriented samples of muscovite-chlorite slates and phyllites were collected by the writer between Jasper and Yellowhead Lake from a variety of stratigraphic levels and structural positions in the Old Fort Point and Wynd Formations. The geographic location and stratigraphic level of the samples are given in Figure 57 and Table 15.

It was also decided to date some samples from an area of higher grade metamorphism farther to the west. Two samples, a pelite and a psammite, were collected from an outcrop a few miles west of Mount Robson Station, British Columbia (Figure 58). This locality is on the western edge of the Main Ranges, just east of the Rocky

TABLE 15: Radiometric Age Determinations

Source	AK No.	Rock Type	Stratigraphic Position	Material Dated	K_2O per cent	Ar^{40}/K^{40}	Date*(m.y.)
Steiner (1962)	362	Conglomeratic sandstone	Basal Jasper	Muscovite separate	8.51	0.0825	1046
	363	Pebble conglomerate	Basal Miette	Muscovite separate	8.79	0.1744	1776
	364	Same sample as 363		Muscovite separate	6.27	0.1083	1288
	365	Medium-grained sandstone	50' below top of Old Fort Point	Muscovite separate	4.67	0.1600	1680
Evans (1961)	182	Slate	150-450' below top of Old Fort Point	Whole rock	3.53	0.0224	346
	184	Slate	200' below top of Old Fort Point	Whole rock	4.11	0.0182	286
	187	Slate	150-450' below top of Old Fort Point	Whole rock	4.18	0.0213	333
Weiner (1966)	370	Slate	2000' above base of Miette	Whole rock	5.14	0.0346	485
	371	Slate	200' above base of Miette	Whole rock	5.78	0.0172	271
	372	Slate	100' above base of Miette	Whole rock	2.09	0.0188	297
	374	Slate	1200' above base of Miette	Whole rock	4.99	0.0187	296
	375	Slate	150' above base of Miette	Whole rock	6.09	0.0192	299
	376	Slate	50' below top of Old Fort Point	Whole rock	4.60	0.0269	408
	377	Slate	500' above base of Miette	Whole rock	5.03	0.0246	377
	662	Phyllite	600' below top of Old Fort Point	Whole rock	4.95	0.0182	286
	663	Phyllite	600' below top of Old Fort Point	Whole rock	4.57	0.0151	240
	661	Phyllite	Miette	Whole rock	10.58	0.0042	69
	659	Medium-grained sandstone	Miette	Biotite separate	8.47	0.0056	93
	660	Same sample as 659		Muscovite separate	10.01	0.0064	105

*Assumed deviation in date is ± 5 per cent

Source	AK No.	Rock Type	Stratigraphic Position	Material Dated	K_2O per cent	Ar^{40}/K^{40}	Date*(m.y.)
Stauffer (1961)	Lead-alpha date	Fine-grained sandstone	Miette	Zircon separate			1330

Mountain Trench. The rocks of this area are probably the stratigraphic equivalents of the Precambrian strata near Jasper, 50 miles to the east (Sorensen, 1955). They are of a higher metamorphic grade and biotite and muscovite are the common micaceous minerals. Chlorite, universally present in the Jasper area, was not observed in these two samples.

Preparation of Samples

Whole Rock For the Ar^{40} and K determinations on the pelitic rocks, a portion of each sample was crushed and sieved, the 35-45 mesh (0.50-0.35 mm) fraction being retianed. Because each particle is an aggregate of many smaller sized mineral flakes, the size employed is of no fundamental significance. Descriptions of the samples will be found in Appendix C.

Mica Separates To obtain the muscovite and biotite separates, a sample of psammite was crushed in a mechanical jaw crusher and run through a Braun Pulverizer. The material was then sieved and the 80-120 mesh (0.177-0.125 mm) fraction retained. Muscovite was separated magnetically from biotite in a Frantz Isodynamic Separator but a large amount of contamination remained in the form of quartz and feldspar grains. These were eliminated by shaking small portions of each separate on an inclined paper towel. Some handpicking under a binocular microscope and a final magnetic separation yielded separates of high purity.

Analytical Procedures

Details of the analytical procedures in the potassium argon method of age determination can be found in Goldich et al. (1961). Potassium determinations were by

the gravimetric method using sodium tetraphenol boron ($NaB(C_6H_5)_4$) precipitation. K^{40} content was calculated from the potassium analyses by using the abundance ratio $K^{40}/K = 0.0118$ atomic percent. Ar^{40} in the samples was determined by the isotope dilution method using a spike containing a known amount of Ar^{38}. The flux-fusion method was employed to extract and purify the argon in the sample. The argon was then analyzed in a 6 inch 60° Nier type mass spectrometer in the Department of Physics, University of Alberta, Edmonton.

Constants used in calculating the radiometric dates were:

$$0.589 \times 10^{-10}/\text{yr.}$$

$$4.76 \times 10^{-10}/\text{yr.}$$

Results

The results are listed in Table 15. The whole-rock samples and muscovite separates from the muscovite-chlorite rocks of the Jasper area yielded K-Ar dates ranging from 1780 to 240 m.y. Muscovite and biotite separates from the Mount Robson area psammite yielded dates of 105 and 93 m.y. respectively, whereas the fine-grained phyllite whole-rock specimen gave 69 m.y. A number of factors can be cited as contributing to this widespread variation.

Interpretations

<u>Variation of K-Ar Date with Grain Size</u>

Variations in original grain size appear to have been one of the most important factors in determining the K-Ar age of samples. Steiner (1962), in an attempt

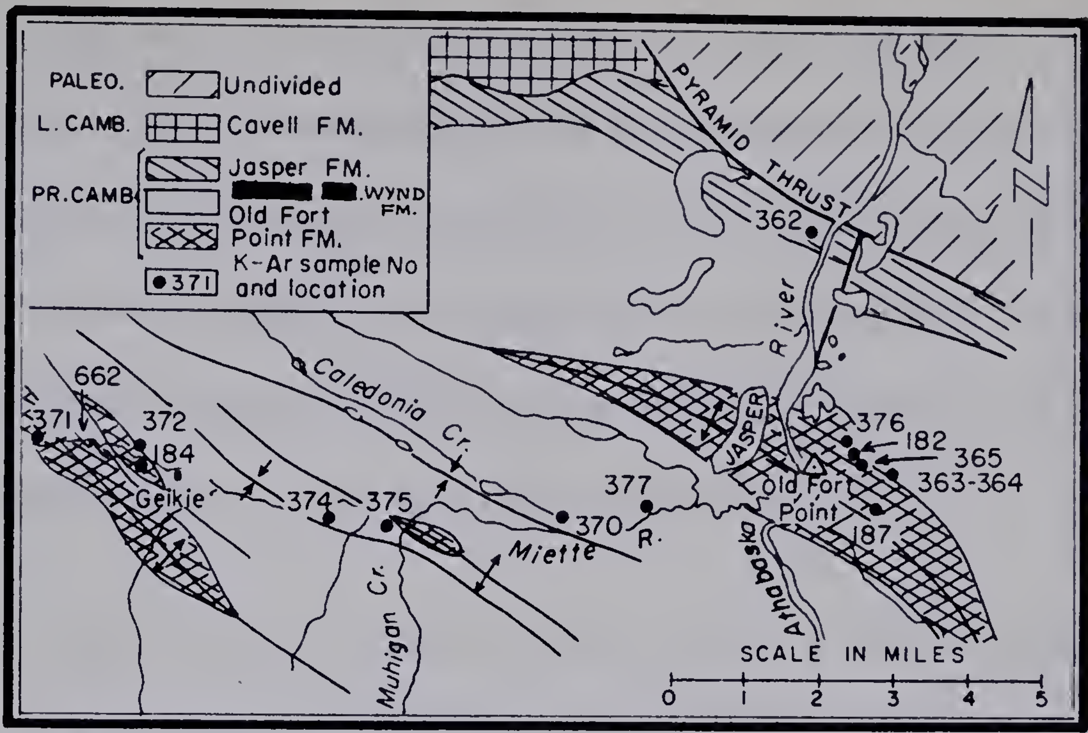


FIGURE 57 GENERALIZED GEOLOGIC MAP OF THE JASPER AREA, SHOWING LOCATIONS OF DATED SAMPLES.

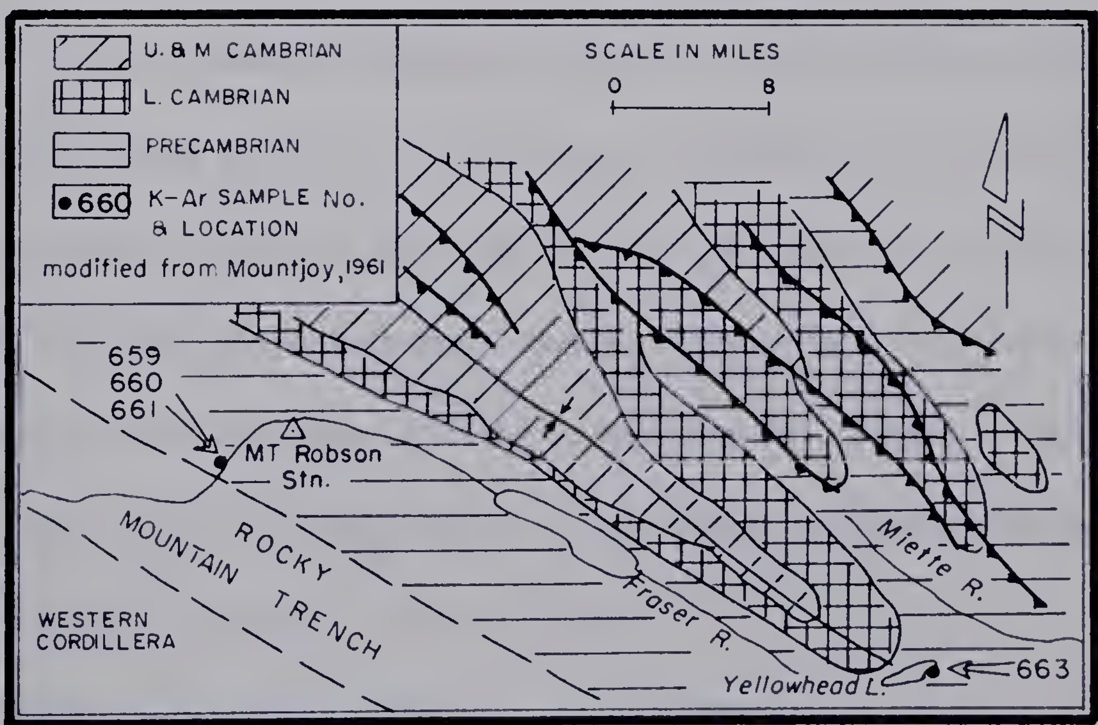


FIGURE 58 GENERALIZED GEOLOGIC MAP OF THE YELLOWHEAD LAKE — MT. ROBSON AREA, SHOWING LOCATIONS OF DATED SAMPLES.

to ascertain the age of the source terrain, dated relatively large muscovite flakes (0.1 to 4.0 mm) oriented in the bedding planes of arenaceous rocks from the Jasper area. These flakes were assumed to be of detrital origin and could be separated from the smaller (less than 0.1 mm) flakes oriented in the cleavage plane. Each of the four dated separates consisted of a different size fraction, two being from the same sample. The apparent ages ranged from 1776 to 1046 m.y.

Steiner observed that if a function of the cube of the median diameter of the mineral grains is plotted against the K-Ar age, a seemingly straight-line function is indicated, age decreasing with decreasing grain size (Figure 59). Evans' whole-rock samples were found to lie along the same straight line, suggesting that the 286 to 346 m.y. whole-rock dates are related to the 1046-1776 m.y. detrital ages. If the straight-line function mentioned is valid, then one could expect the radiometric argon loss to increase during metamorphism with a decrease in particle size. Although the cube of the median diameter indicates a volume function, the rapid decrease of the ratio of surface area to volume, with decreasing diameter, also has to be considered. Hart (1960) observed a decrease of K-Ar age with grain size for muscovites separated from a metamorphosed Vermont marble. This writer has plotted the results of nine whole-rock determinations from the Jasper area on Steiner's diagram (Figure 59). They range in age from 240 to 485 m.y. and group with Evans' whole-rock samples. This evidence supports Steiner's thesis.

The linear relationship described above should hold until a critical grain size is approached. The line will then tend to flatten out at a time value equivalent to the "true" age of metamorphism. Before this critical size is reached, progressively

FIGURE 59

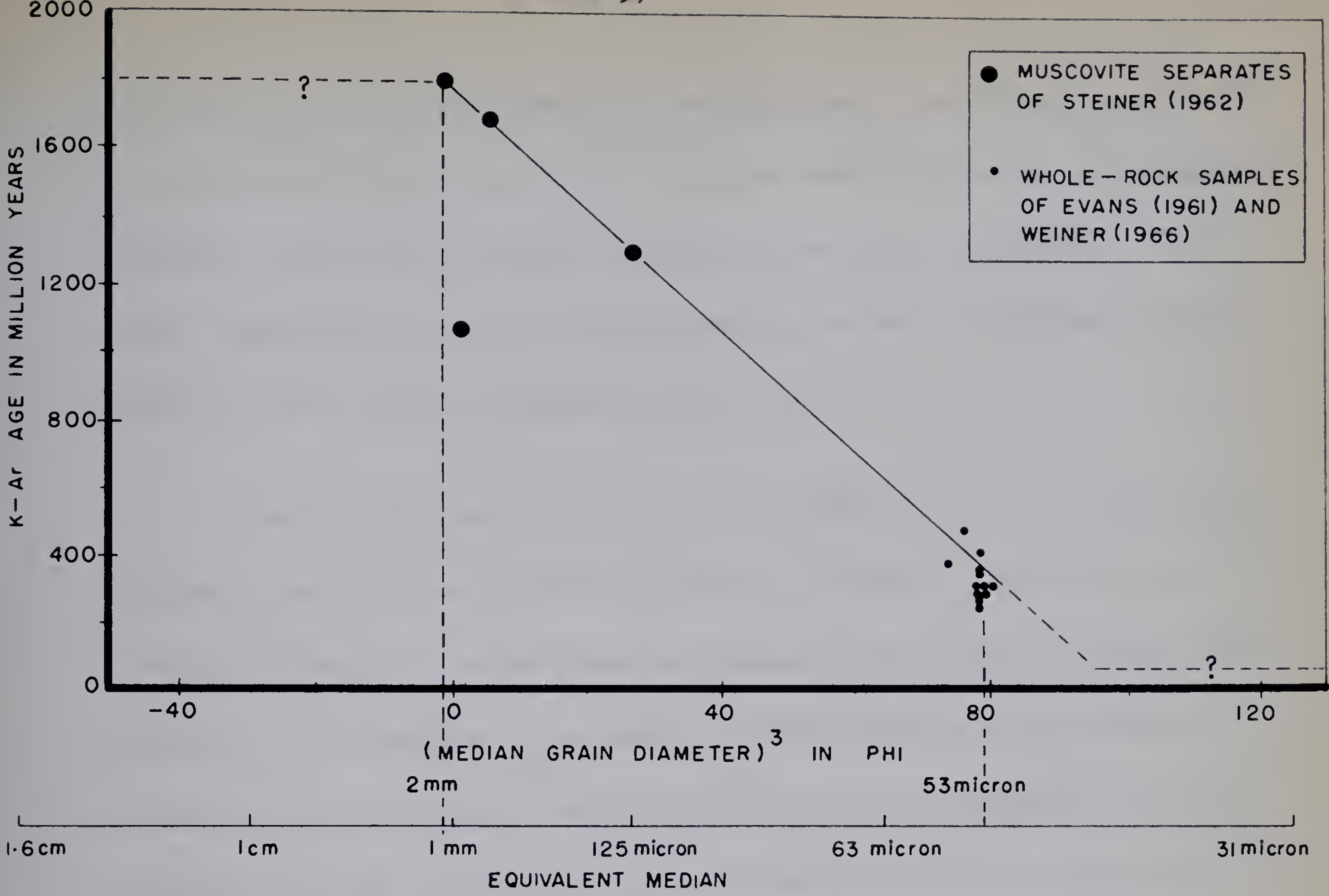
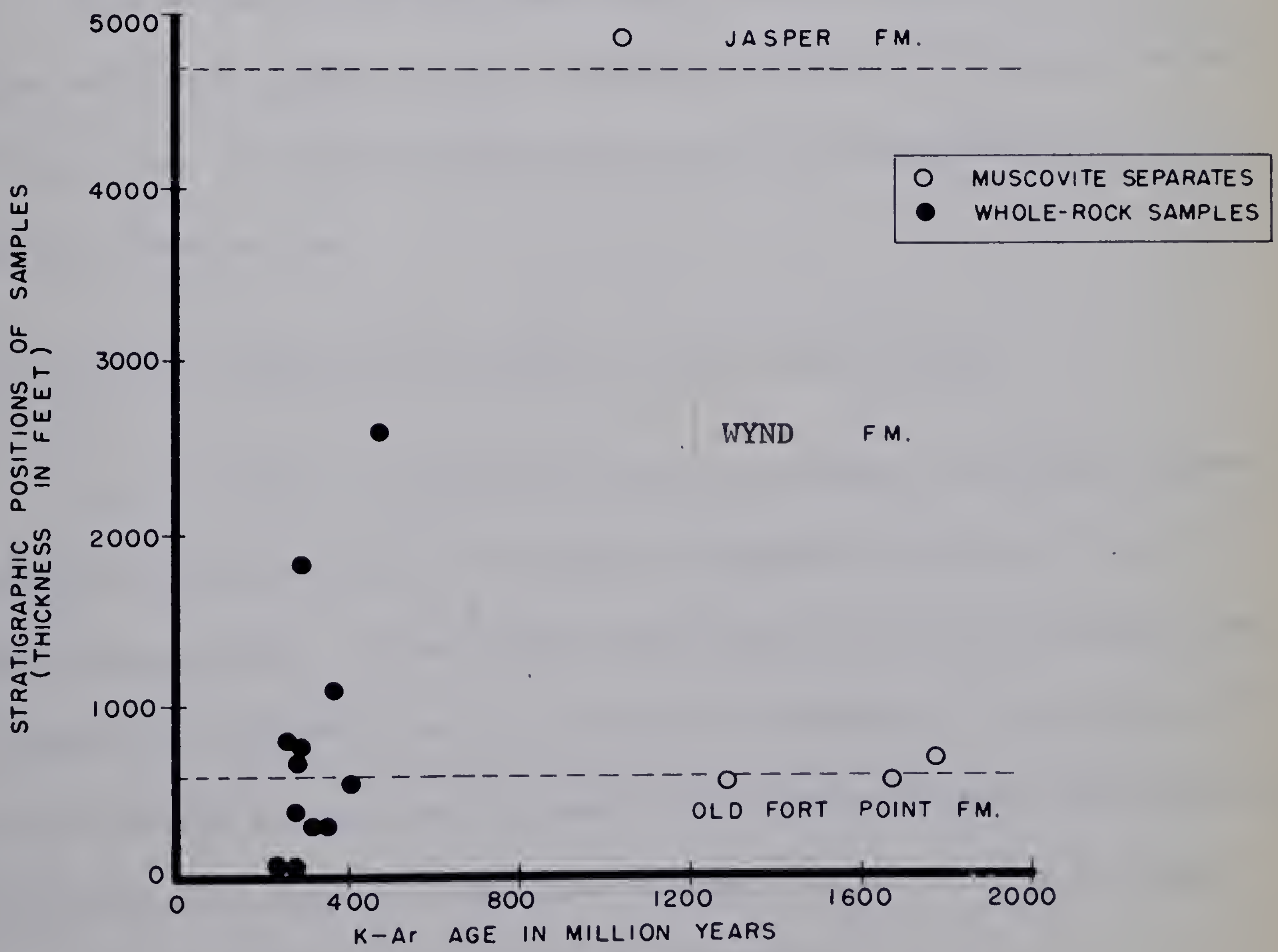


FIGURE 60



smaller grains should yield progressively younger dates; beyond this point, all grain sizes should yield the same date. An attempt was made by this writer to disaggregate whole-rock samples with the idea of dating the finest clay-sized fraction. Unfortunately, repeated freezing and thawing of samples, as well as prolonged periods of boiling in water, failed to disaggregate the samples.

If the age of the source terrain was about 1700 m.y., then the straight line in Figure 59 would flatten out at the upper end as indicated. In order to see if this flattening did exist, this writer attempted to separate micas larger than those dated by Steiner. This attempt was unsuccessful. Stauffer (1961) also attempted to determine the age of the source terrain of the Precambrian of the Jasper area. A lead-alpha date was run on detrital zircons and an age of 1330 m.y. obtained.

Because the dates from the Mount Robson area were obtained from rocks of higher metamorphic grade, they were not plotted on Figure 59 with the samples from the Jasper area. It should be noted, however, that the finer grained sample again yielded the younger date.

Variation of K-Ar Dates with Orientation of Mica Along Cleavage

Evans' (1961) X-ray diffraction studies of three whole-rock samples suggested that K-Ar age decreased with an increase in the degree of orientation of muscovite along cleavage planes. The orientation index (Chapter 3) of mica in cleavage planes was taken as an indicator of intensity of dynamic metamorphism. If one assumes that, as slaty cleavage was developed to a greater degree more and more mica recrystallized in the plane of cleavage, it is reasonable to expect that loss of radiogenic argon would increase with increasing cleavage development.

Study by this writer of nine additional slate and phyllite samples casts serious doubt on the validity of the orientation index as an approximate indicator of the amount of radiogenic argon loss that a sample has experienced. In Figure 61, the results of the orientation index determinations are plotted against the Ar^{40}/K^{40} ratio of the samples. The scatter of points is so large as to rule out any conclusion concerning the existence of a reciprocal relationship between orientation index and Ar^{40}/K^{40} ratio.

If one assumes that the orientation index is a valid indicator of the intensity of dynamic metamorphism, then the scatter of points might be explained by expected variations from sample to sample. Grain size may be a factor in determining the degree of slaty cleavage development (Chapter 3).

A second attempt at correlating slaty cleavage development with radiometric date was based on a comparison of the Ar^{40}/K^{40} ratio to the ratio of the amount of mica in the cleavage plane over that in the total sample. With an increase in cleavage development, there should be an increase in the latter ratio. Estimates of the amount of mica were made for four muscovite-chlorite whole-rock samples in which bedding and cleavage was oblique. The methods used are those outlined in Chapter 3. The limited number of points in Figure 62 suggests a reciprocal relationship - Ar^{40}/K^{40} ratio decreasing with an increase in the relative amount of mica in the cleavage. Variations in original grain size would tend to obscure this suggested relationship.

The phyllite sample from the Mount Robson area which yielded the youngest date of all (69 m.y.) has about 95 percent of the mica oriented in or near the cleavage plane.

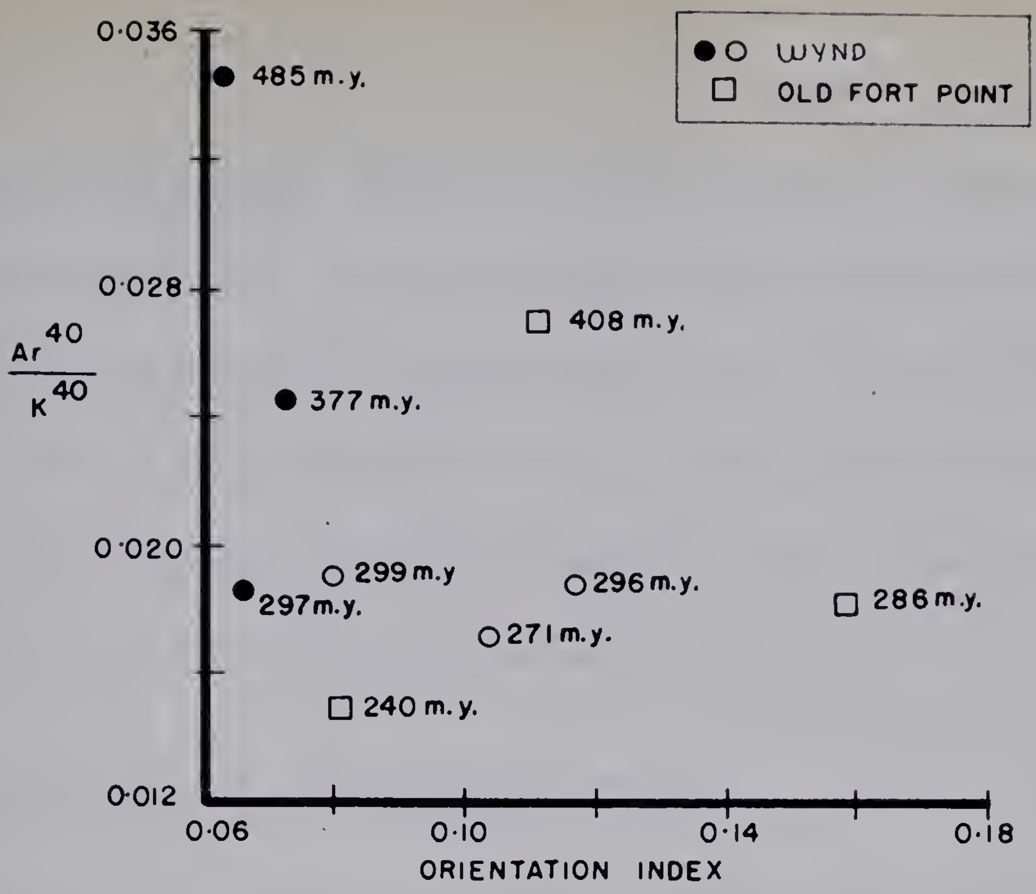


FIG. 61 Ar^{40}/K^{40} RATIO VS. ORIENTATION INDEX. OPEN CIRCLES AND SQUARES DESIGNATE THE ORIENTATION INDICES OF MUSCOVITE ALONG CLEAVAGE PLANES IN SAMPLES WHERE BEDDING AND CLEAVAGE ARE OBLIQUE. CLOSED CIRCLES INDICATE A COMPOSITE ORIENTATION INDEX, BEDDING AND CLEAVAGE BEING PARALLEL.

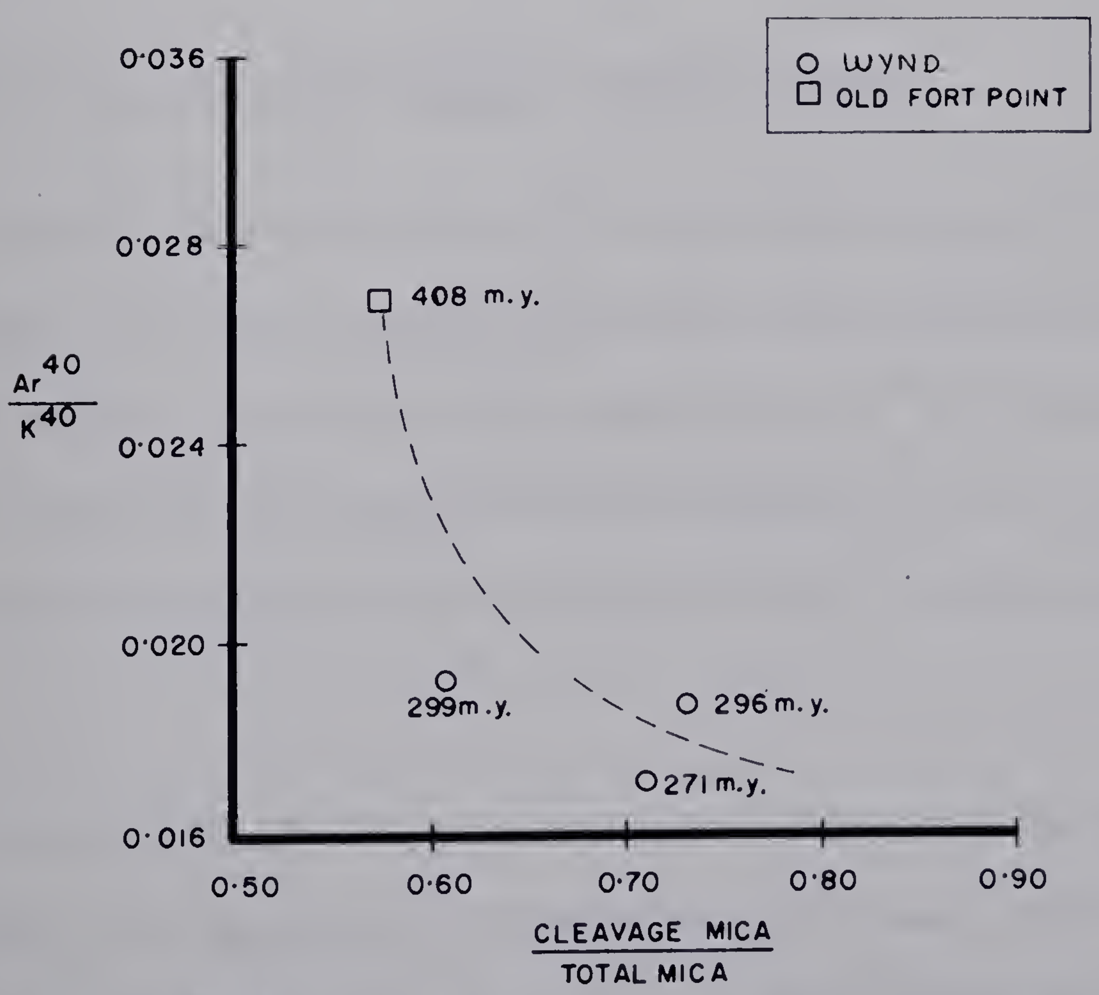


FIG. 62 Ar^{40}/K^{40} RATIO VS. VARIATION OF AMOUNT OF MUSCOVITE IN PLANE OF CLEAVAGE TO THAT IN TOTAL SAMPLE.

The picture emerges, therefore, of the muscovite in a whole-rock pelite sample consisting of: (1) "new" mica recrystallized parallel to the cleavage which has lost all or virtually all of its premetamorphic argon, (2) mechanically oriented cleavage mica which has lost some of its argon and (3) mica still oriented in or near the plane of bedding which has lost some of its argon. These three different types of micas would contribute to a single whole-rock date.

Variations of K-Ar Date with Stratigraphic Position

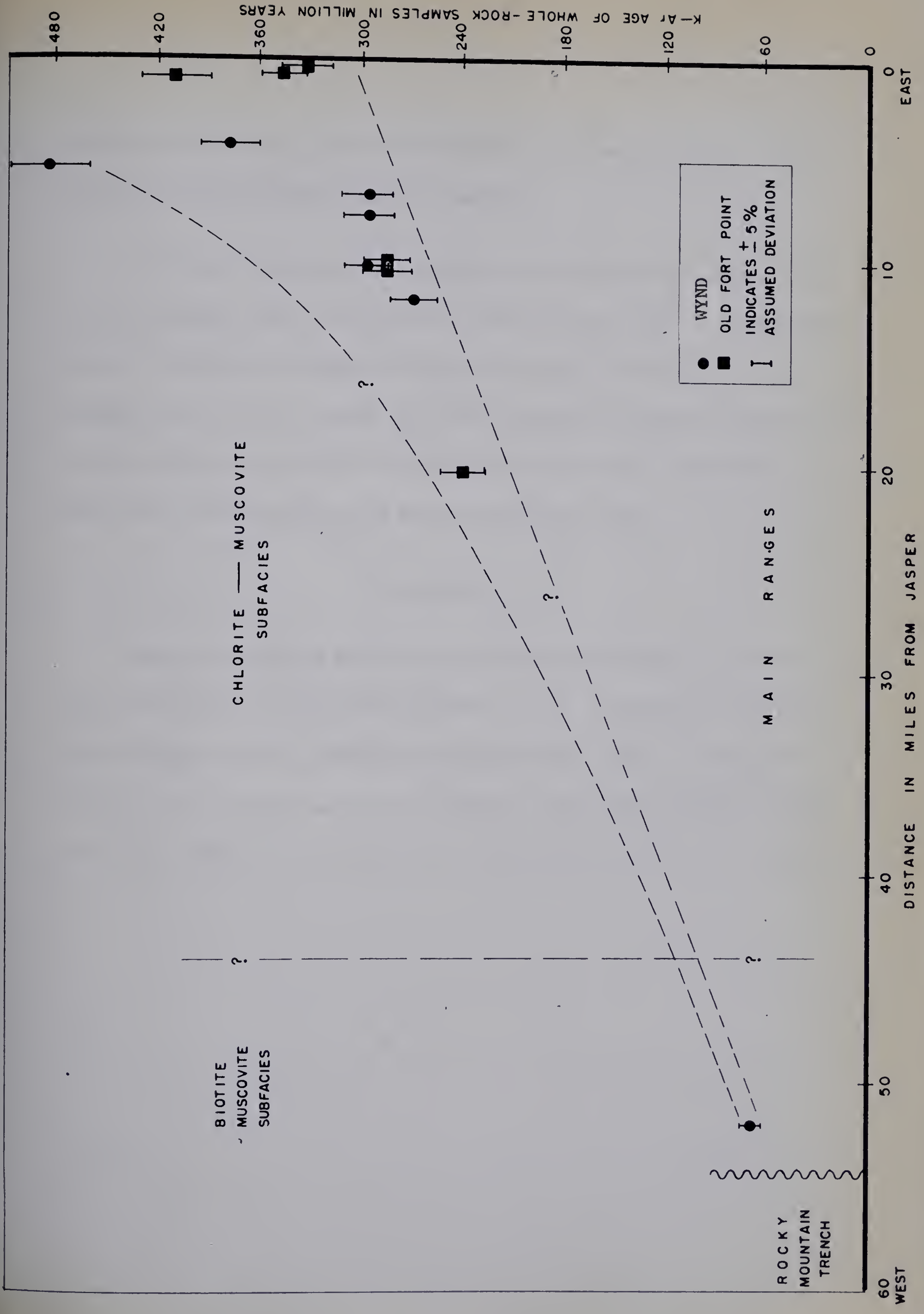
Although about 5000 feet of section separate the highest and lowest samples, no correlation was found between stratigraphic level and radiometric date (Figure 60). Other factors, e.g. variations in grain size, were of greater importance in causing argon loss.

Variation of K-Ar Date with Geographic Location of Sample

Figure 63 illustrates variation in K-Ar date with increasing distance westward from Jasper. The samples are distributed along a 50 mile east-west traverse across the Main Ranges. The traverse makes an angle of about 40° with the tectonic strike (Figures 57 and 58). The indicated boundary between the chlorite-muscovite and the biotite-muscovite subfacies in Figure 61 is purely illustrative and not located in the field.

In spite of the 30 mile gap in sampling from Yellowhead Lake to the Mount Robson area, there appears to be a somewhat orderly decrease in radiometric date from east to west for the whole-rock samples. Therefore, the variation in whole-rock dates may be largely a reflection of an increase in intensity of regional meta-

FIGURE 63


K-Ar AGE OF WHOLE-ROCK SAMPLES IN MILLION YEARS
480
420
360
300
240
180
120
60
0
DISTANCE IN MILES FROM JASPER
0 EAST
10
20
30
40
50
60 WEST
WYND
OLD FORT POINT
INDICATES ± 5%
ASSUMED DEVIATION
CHLORITE —— MUSCOVITE
SUBFACIES
BIOTITE
- MUSCOVITE
SUBFACIES
MAIN RANGES
ROCKY
MOUNTAIN
TRENCH
?
?
?
?

morphism toward the west. The westernmost and youngest sample (69 m.y.) would then be the nearest approach to complete updating.

Transitional zones of varying radiometric date have been reported in studies of other matmorphic areas. Long and Kulp (1962) and Long (1962) found transitional zones in the Manhattan and Reading Prongs and in nearby Dutchess County, New York. In western North Carolina, Long et al. (1959) recognized a transition of apparent ages from 355 to 890 m.y. occurring in the same rock unit (Cranberry Gneiss) along a 10 mile traverse across the strike of the border of a 350 m.y. event.

Conclusions

Radiometric dating of detrital muscovite indicates that the source terrain of the Jasper Precambrian was at least 1776 ± 90 m.y. old. Aside from the fact that most whole-rock samples yielded dates ranging from 485 to 240 m.y. (Ordovician through Permian), evidence supporting a Paleozoic thermal metamorphism is lacking in the area. Folding and metamorphism occurred sometime later than 70 m.y. ago.

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Appendix A

Locations of Measured Sections of the Old Fort Point Formation

<u>Tekarra Creek</u> (Figure 1) 117°59'15"W, 52°49'18"N

Located 3.6 miles, S 40° E of Old Fort Point. Outcrops are astride the southeast extension of the Jasper Anticlinorium and are located in the creek bed. Partial sections of Members B and D are exposed along with a complete section of Member C.

<u>Portal Creek Anticlinorium</u> (Figure 49) 118°02'30"W, 52°47'50"N

Located 5 miles, S 10° E of Old Fort Point and one quarter mile southeast of Portal Creek bridge on the Banff-Jasper Highway. Poor exposures along the hillside. Partial sections of Members B, C and D are exposed.

<u>Mina Lake</u> (Evans, 1961, Figure 7) 118°07'30"W, 52°53'30" N

Located 0.5 miles, N 55° W from the northwestern corner of Mina Lake. Outcrops form low hill. Partial section of Member B is exposed.

<u>Muhigan Creek Anticlinorium</u> (Figure 50) 118°11'30"W, 52°51'30"N

On Yellowhead Road (Highway 16) 5.3 miles due west of the junction of Yellowhead Pass Road and the Banff-Jasper Highway. Outcrops are on the south side of the road. Partial sections of Members B, C and D are exposed.

<u>Meadow Creek Anticlinorium</u> (Figure 10) 118°16'00"W, 52°52'00"N

Located about 8.5 miles due west of Jasper townsite. Good exposures along the Yellowhead Road, the Canadian National Railways right-of-way and Meadow Creek allow the construction of complete composite section of the Old Fort Point Formation.

Meadow Creek Formation crops out along banks of Meadow Creek about 1.2 miles southwest of the confluence of Meadow Creek and the Miette River. The base of the Meadow Creek Formation is not exposed.

Yellowhead Lake Anticlinorium (Figure 53)

Located 19 miles west of Jasper townsite on Yellowhead Road. Partial sections of Members A and B are exposed on hillsides on the south side of the road.

Appendix B

Description of Computer Programs Used in Structural Analysis

A modern high-speed digital computer was used to treat some of the data collected in the field. The programs employed were originally written by Muecke (1964) in Fortran II for an IBM 1620 Data Processing System in the Computing Sciences Center of the University of Alberta, Edmonton. They were subsequently rewritten by Cruden (1966) and Yanda in Fortran IV when an IBM 7040 system was installed at the University. A brief resumé of each program is given below. Details of each program can be found in Muecke (1964) and Cruden (1966). Copies of the programs can be obtained from the Department of Geology at the University.

Pole Density Diagram: Program 45001

Pole densities are counted out on a reference sphere and are then projected onto an equatorial plane. True pole densities are thus obtained in contrast to the more commonly used procedure of counting out on the equatorial plane of the reference sphere. Output consisted of 2 grids of numbers, circumscribed by a 10 inch diameter circle. One grid consisted of the percentage of points per 1% area, the other showed the distribution of the actual number of points per 1% area. The grids were contoured by hand. This particular program was used to prepare diagrams showing the distribution of S_1, S_2, S_3 and joints. It is also capable of handling lineations such as L_{1x2}.

Determination of Mean Planes: Program 450002

Determination of mean planes was realized by using the statistical treatment

of dispersion of points on a sphere according to the method of Fisher (1953). Individual maxima on a pole diagram, or groups of data not used in pole density diagrams, can thus be analyzed. For each data set a mean value, the confidence radius about the mean, and the dispersion are calculated. This program was used to treat S_1 and S_2.

Determination of Beta Axes: Program 45003

If s-surfaces are folded cylindrically, their intersections will tend to cluster about a mean value, known as the B-axis. It defines the axis of folding. The equation $n\frac{(n-1)}{2}$ gives the total number of mutual intersections of n number of non-parallel planes. Since 25 planar measurements yield 300 intersections an investigator must limit the size of his data sets if he is using the ordinary graphical method. The computerized method does not suffer this limitation and hence large data sets, if available, may be treated. The B-axis is found by calculating the vector sum of all the individual intersections. The confidence radius and a precision parameter (Watson, 1956) are also calculated.

Appendix C

Description of Samples Dated by K-Ar Method

AK-370: Silty slate; color dark bluish-grey; bedding and cleavage parallel; composition 80% muscovite and chlorite, 20% quartz and feldspar; size of muscovite flakes up to 0.80 mm for larger ones, smaller ones 0.015 mm or less.

AK-371: Slate with silty laminae; color light, greenish-grey, laminae rusty; cleavage well developed, parallel to bedding; composition 80% muscovite and chlorite, 20% quartz and feldspar; size of muscovite flakes up to 0.09 mm for largest, smaller ones 0.015 mm or less.

AK-372: Silty slate; color light green; bedding and cleavage parallel; composition 30% silt-sized quartz and feldspar grains, 70% muscovite and chlorite; size of muscovite flakes up to 0.21 mm most about 0.06 mm.

AK-374: Slate; color dark, bluish-grey; cleavage well developed, oblique to bedding; composition 85% muscovite and chlorite, 15% quartz and feldspar; size of muscovite flakes up to 0.1 mm for some oblique to cleavage, most less than 0.03 mm.

AK-375 Slate; color dark, greenish-grey; cleavage well developed, oblique to bedding; composition 80% muscovite and chlorite, 20% quartz and feldspar; size of muscovite flakes up to 0.05 mm for largest, smallest less than 0.015 mm.

AK-376: Slate; color medium grey; cleavage well developed, oblique to bedding; composition 85% muscovite and chlorite, 15% quartz, feldspar and calcite; size of muscovite flakes up to 0.03 mm for largest, most 0.015 mm or less.

AK-377: Slate; color medium, greenish-grey; cleavage and bedding parallel; composition 80% muscovite and chlorite, 20% quartz and feldspar; size of muscovite flakes up to 0.08 mm, most less than 0.015 mm.

AK-661: Phyllite; color medium to light grey, brown biotite flakes on cleavage surfaces; cleavage well developed and oblique to bedding; composition 85% muscovite, 5% biotite, 10% quartz and feldspar, chlorite not observed; flakes of muscovite and biotite have well defined outlines and are oriented parallel or subparallel to cleavage; size of muscovite flakes from 0.01 to 0.12 mm, biotite flakes from 0.03 to 0.30 mm.

AK-662: Phyllite; color medium, greenish-grey; cleavage extremely well developed, rock splits readily into sheets less than 1 mm thick, cleavage kinked by F_2 folding, bedding oblique to cleavage but can't be recognized in hand specimen; composition principally muscovite and chlorite, quartz and feldspar very minor.

AK-663: Phyllite; color greenish-grey, with rusty spots due to weathered siderite; cleavage kinked by F_2 folding; composition principally muscovite and chlorite, lesser amounts of quartz, feldspar and siderite, the latter occurring in grains up to 2 mm in diameter around which cleavage is bent.

EXPLANATION OF PLATE I

Outcrop Photographs Showing Sedimentary Features and Igneous Intrusive

Figure

1 - Conformable contact between slates of Member D of Old Fort Point (O.F.P.) and arenites of the Wynd Formation (W.) in the Meadow Creek Anticlinorium. The strata are overturned. Outcrop is along Canadian National Railways tracks 5000 feet west of Geikie Station.

2 - Interbedded slates and silty slates of Member D, Old Fort Point Formation, in abandoned quarry on southwest limb of Muhigan Creek Anticlinorium about 400 feet east of bridge across Muhigan Creek.

3 - Argillaceous limestone-breccias of Member B, Old Fort Point Formation at east end of bridge across Athabasca River near Old Fort Point. Note abundance and size range of the phenoclasts. White bands are calcite veins.

4 - Rhythmic interbedding of limestones (light beds) and calcareous slates (dark beds) of Member B_3, Old Fort Point Formation, Meadow Creek Anticlinorium. Outcrop is along Canadian National Railways tracks 2400 feet west of Geikie Station.

5 - Argillaceous limestone-breccia of Member B, Old Fort Point Formation near east end of bridge across Athabasca River at Old Fort Point. Note the paucity of phenoclasts compared to Figure 3. Bedding in this outcrop is almost vertical, bottom of the breccia is toward the right.

6 - Basal siltstones and slates of Member B of the Old Fort Point Formation resting discordantly on the upper siltstones of Member A (to right of the hammer). Beds dip to the right and are overturned. Outcrop at east end of bridge across Athabasca River near Old Fort Point.

7 - Igneous intrusive on the Yellowhead Road in the Meadow Creek Anticlinorium (Figure 10). The light colored materials are veins consisting largely of quartz.

8 - Discordant contact of the igneous intrusive shown in Figure 7 with limestones of Member B_3 of the Old Fort Point Formation.

PLATE I.

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EXPLANATION OF PLATE II

Hand Specimen Photographs Showing Sedimentary Features

Figure

1 - Arenaceous limestone-breccia from Member C_2 of the Old Fort Point Formation of the Jasper Anticlinorium. The phenoclasts are of dark bluish-grey limestone, whereas the matrix consists largely of quartz sand grains and calcite cement. Surface etched with HCl to emphasize the details. Sample is from outcrop on hillside north of Jasper townsite.

2 - Quartz-pebble limestone-breccia from Member D of the Old Fort Point Formation, Portal Creek Anticlinorium. Phenoclasts are of dark bluish-grey limestone and calcareous sandstone.

3 - Arenaceous limestone-breccia from Member C_2 of the Old Fort Point Formation, Meadow Creek Anticlinorium. The phenoclasts are randomly oriented and are dark bluish-grey or medium grey in color.

4 - Incipient brecciation in bedded limestones from Member B_3 of the Old Fort Point Formation, Jasper Anticlinorium. The light colored beds are limestone; thinner darker beds are calcareous slate. This sample is from the upper part of Member B_3 in section along the Athabasca River (Evans, 1961, p. 8).

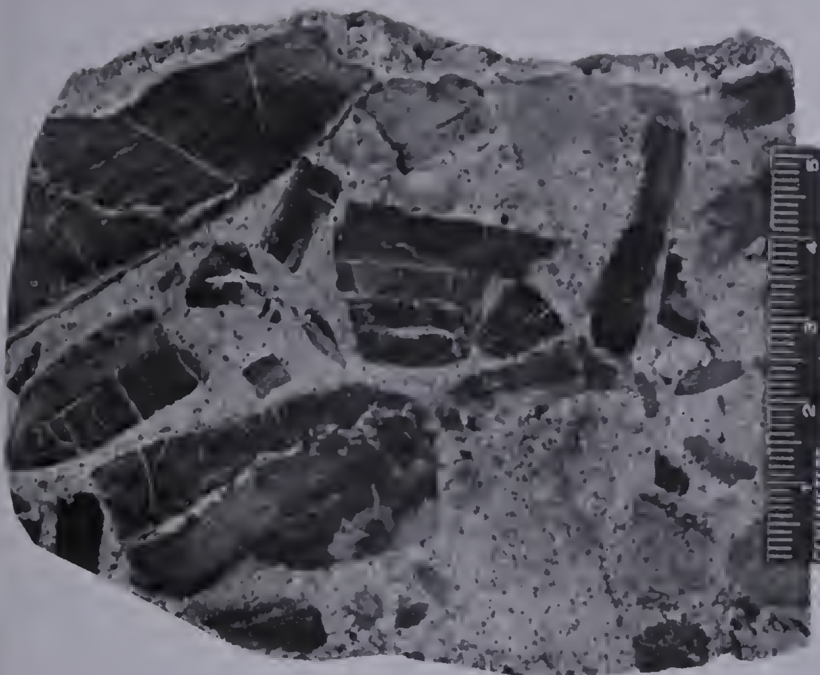
5 - Arenaceous limestone-breccia from Member C_2, Old Fort Point Formation, Meadow Creek Anticlinorium. Preferred orientation of the limestone phenoclasts is due in part to deformation.

6 - Bedded limestone from Member B_3, Old Fort Point Formation, Meadow Creek Anticlinorium. The arrow indicates "way up". Light colored limestone has filled in trough between what appears to be ripple marks developed in a very silty limestone. Sample is from outcrop along Canadian National tracks about 2400 feet west of Geikie Station.

7 - Arenaceous limestone-breccia from Member C_2, Old Fort Point Formation, Meadow Creek Anticlinorium. The sample is from overturned limb of an anticline and the limestone phenoclasts have experienced marked thinning and reorientation. For details of the calcite fabric, see Plate IX-6, 7 and 8. Sample is from most westerly outcrop of Member C_2 on north side of Meadow Creek (Figure 10).

8 - Bedding surface of calcareous siltstone from Member B of the Old Fort Point Formation, Mina Lake section. Features believed to be similar to the linguoid or cuspate ripple marks found in recent tidal flats.

PLATE II.



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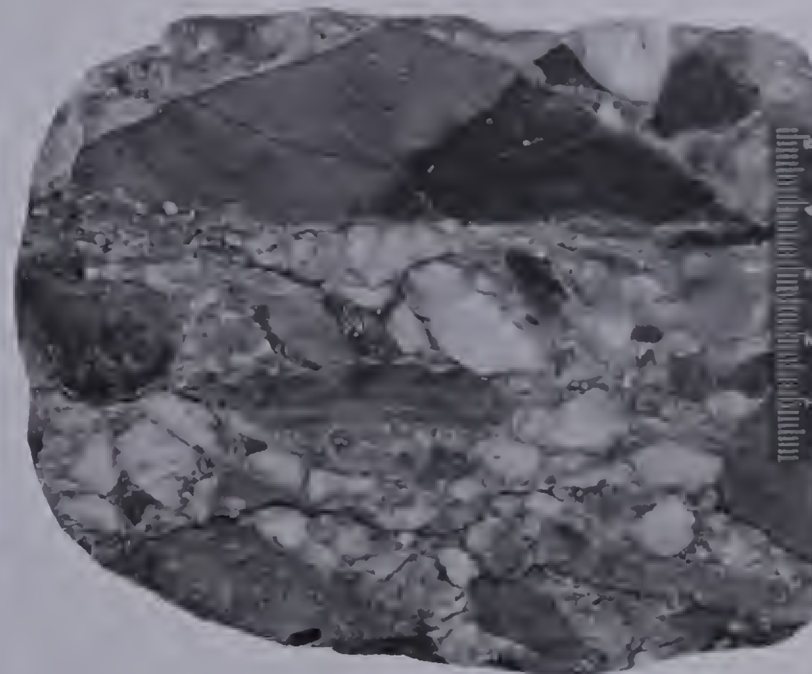

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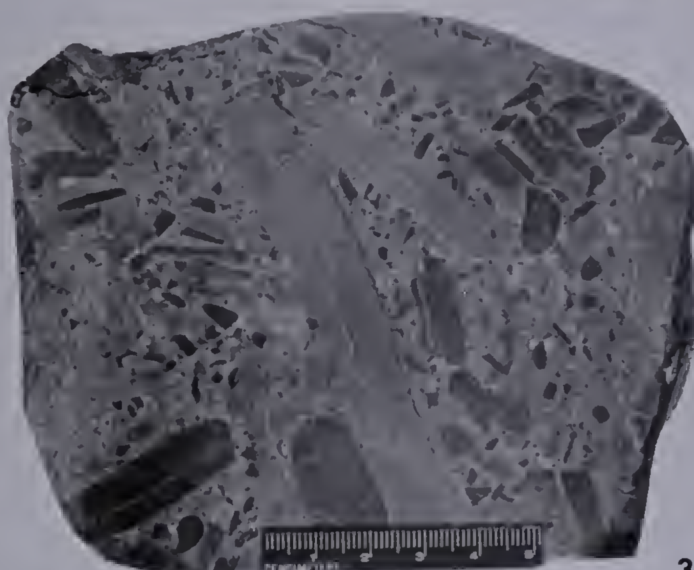

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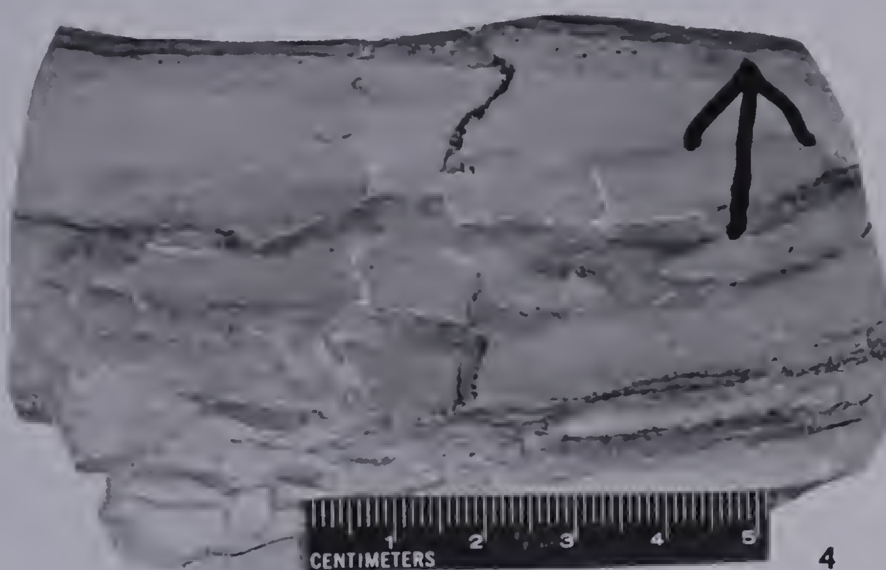

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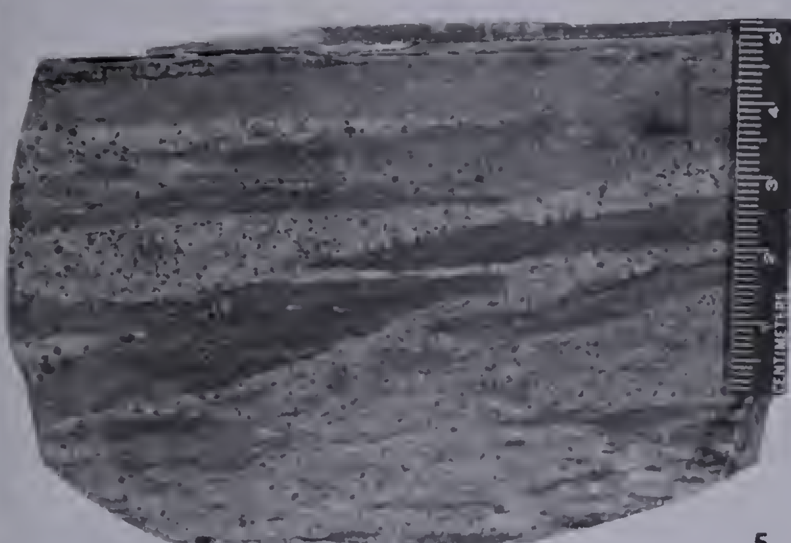

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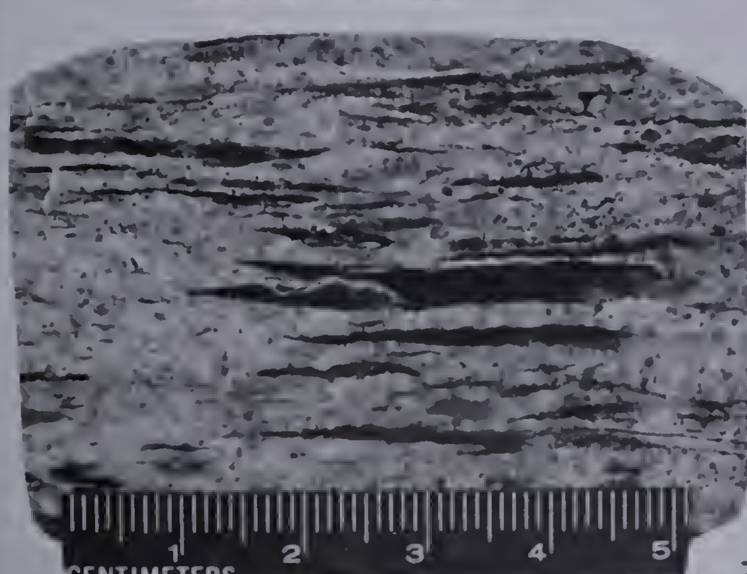

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EXPLANATION OF PLATE III

Outcrop Photographs Showing Topography and Folding

Figure

1 - View westward from near Geikie Station showing the typical topography of the Wynd (W) and Old Fort Point (O.F.P.) Formations in the Meadow Creek Anticlinorium. The heavy dashed line indicates the position of a normal fault.

3,4 - Synclines in the competent arenaceous Wynd strata of the central zone of the Meadow Creek Anticlinorium. The folds are approximately concentric in style. They are located on the north side of Yellowhead Road about 7000 and 8000 feet west of bridge across Miette River (Figure 10).

5 - Overturned syncline in the interbedded limestones and slates of Member B_3 of the Old Fort Point Formation, Meadow Creek Anticlinorium. Note the similar style of the fold. Outcrop is on Canadian National Railways tracks about 6300 feet west of Geikie Station.

6 - Overturned anticline in interbedded limestones (thicker beds) and slates of Member B_3 of the Old Fort Point Formation in the Meadow Creek Anticlinorium. Fold is approximately similar in style. Note relative thickening in hinge zone and thinning of overturned limb. Note the axial plane strain-slip cleavage. Displacements along cleavage on the overturned limb are of the reverse fault type, those on the normal limb of the normal fault type. Same location as Figure 5.

PLATE III.

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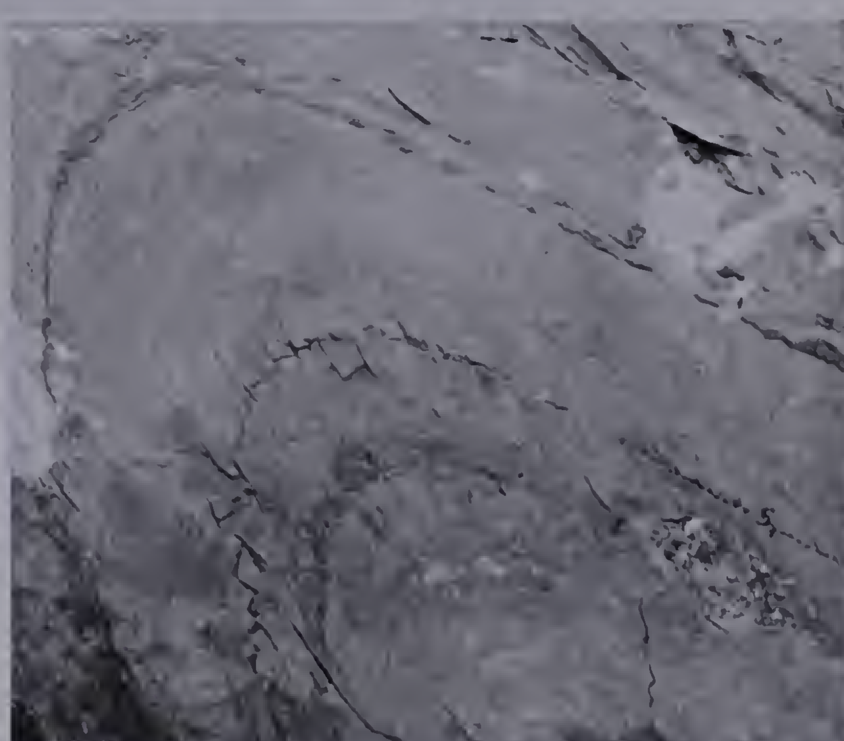

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EXPLANATION OF PLATE IV

Outcrop Photographs Showing Folding and Cleavage

Figure

1 - Syncline in interbedded limestones (ls.) and slates (sl.) of Member B_3 of the Old Fort Point Formation in the Meadow Creek Anticlinorium. Note that the fold is approximately similar in style. Outcrop located on Canadian National Railways tracks about 6300 feet west of Geikie Station.

2 - Overturned anticline in interbedded slates (sl.) and limestones (ls.) of Member B_3 of the Old Fort Point Formation in the Meadow Creek Anticlinorium. The fold is approximately similar in style. Note the relative thickening of the limestones and slates in the hinge zone. Slaty cleavage (S_2) parallels the axial surface of the fold. Same location as in Figure 1.

3 - Slaty cleavage (S_2) in the silty slates of Member B_2 of the Old Fort Point Formation, Meadow Creek Anticlinorium. Note how the bedding S_1 is obscured by the cleavage.

4 - Well-developed slaty cleavage (S_2) in the hinge zone of an anticline in the Member D slates of the Old Fort Point Formation in the Meadow Creek Anticlinorium. Note the penetrative nature of the slaty cleavage. Outcrop is located 6600 feet west of the bridge across Miette River (Figure 10).

5 - Fracture-cleaved Wynd Formation sandstones in the northeast limb of the Meadow Creek Anticlinorium. Note how the cleavage is refracted near the contact of the massive sandstone (ss.) and the interbed of slate (sl.). Outcrop located at west end of bridge across Miette River (Figure 10).

6 - Transition from slaty to fracture cleavage in a small syncline in the slates (sl.) and sandstones (ss.) of the Wynd Formation of the Meadow Creek Anticlinorium. Slaty cleavage (S_2) parallels the axial surface of the fold, but fracture cleavage is almost normal to the bedding (S_1) in the sandstone. Outcrop located along Canadian National Railways tracks about 4800 feet west of Geikie Station.

PLATE IV.

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EXPLANATION OF PLATE V

Outcrop Photographs Showing Cleavage, Kink Folding, and Faulting

Figure

1 - Sigmoidal fracture in limestones of Member B_3 of the Old Fort Point Formation, southwest limb of the Muhigan Creek Anticlinorium. Cleavage dips less steeply in the more argillaceous beds. Outcrop located along Yellowhead Road about 600 feet east of bridge across Muhigan Creek.

2 - Fracture cleavage in vertical sandstones of the Old Fort Point Formation, Member C_2, on the northeast limb of the Muhigan Creek Anticlinorium. Note the displacements that have taken place along the cleavage surfaces. Outcrop located on Yellowhead Road about 1000 feet east of bridge across Muhigan Creek.

3 - Kink folded slaty cleavage (S_2) in Member D slates of the Old Fort Point Formation, Meadow Creek Anticlinorium. Axial surfaces (S_3) of kink folds are, in some cases, fracture surfaces; in other cases, they are zones of sharp bending of S_2. Outcrop located along Yellowhead Road about 3700 feet west of bridge across Miette River.

4 - Kink folds in Member B_2 slates (sl.) of the Old Fort Point Formation, Meadow Creek Anticlinorium. Dotted lines indicate the hinges of the kink folds (S_3-S_2 intersection). Note how the kink folds usually do not penetrate the siltstone (sltst.) bed. Features resembling ripple marks are manifestations of fracture cleavage in the siltstone. Same location as Figure 3.

5 - Closely spaced kink folds in Member B_1 slates of the Old Fort Point Formation, Meadow Creek Anticlinorium. Kink folds are penetrative in this outcrop. Same location as Figure 3.

6 - Closely spaced kink folds in Member B_1 slates of the Old Fort Point Formation, Meadow Creek Anticlinorium. Note the variation in attitude of the kink folds and how they cross one another. Same location as Figure 3.

7 - Tightly folded Wynd slates (sl.) and sandstones (ss.) in central zone of Meadow Creek Anticlinorium. This outcrop is believed to be part of a local zone of decollement between the Wynd and Old Fort Point Formation. Contact strain has caused bending of slaty cleavage on the convex sides of the fold hinges. Outcrop on north side of Yellowhead Road about 6800 feet west of bridge across Miette River.

8 - Southwest dipping normal fault displacing Old Fort Point Formation strata in Meadow Creek Anticlinorium. Footwall consists of tightly folded Member B_3 limestones and slates, hanging wall of overturned beds of Members B and C. Outcrop located along Canadian National Railway tracks about 6300 feet west of Geikie Station.

EXPLANATION OF PLATE [illegible]

Outcrop Photographs Showing Contacts, [illegible] Folding and Faulting

Figure

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PLATE V.

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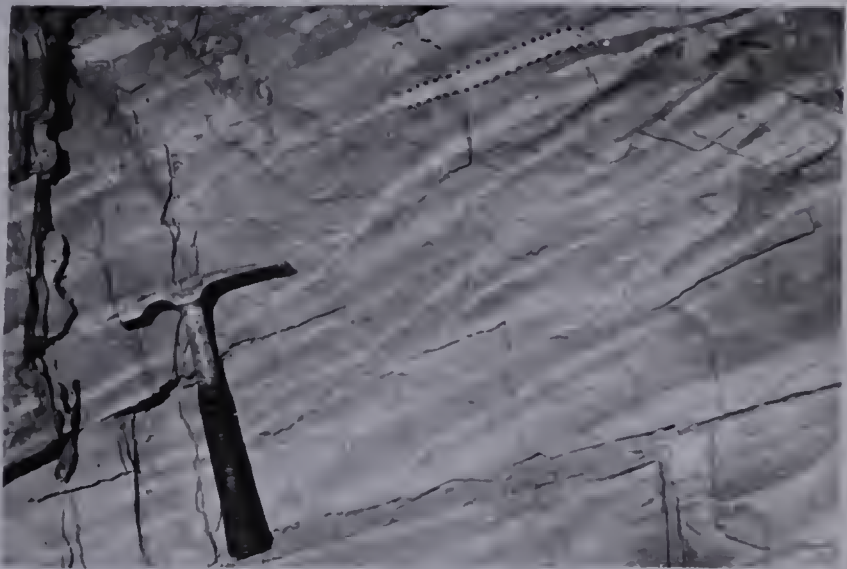

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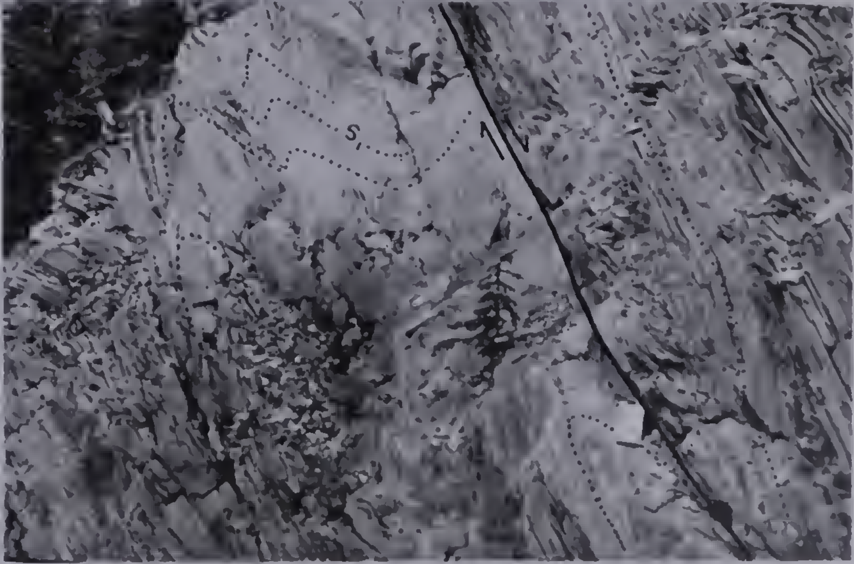

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EXPLANATION OF PLATE VI

Hand Specimen Photographs Showing Cleavage and Kink Folding

Figure

1 - Slip (strain-slip) cleavage in a syncline in interbedded limestones (ls.) and slates (sl.) of Member B_3 of the Old Fort Point Formation from the Meadow Creek Anticlinorium. Note the displacements along cleavage surgaces and minor folding in the slate beds. Sample is from outcrop along Canadian National Railways tracks about 6300 feet west of Geikie Station.

2 - Slaty-cleaved phyllite from the Wynd Formation on the north side of Yellowhead Lake. Note how cleavage wraps around the prominent siderite grains.

3 - Interbedded slate (sl.) and limestone (ls.) from Member B_3 of the Old Fort Point Formation in the Meadow Creek Anticlinorium. Calcite has crystallized in openings created when the cleavage planes were separated during the episode of normal faulting.

4 - Fracture-cleaved Wynd arenite from the northeast limb of the Meadow Creek Anticlinorium. Cleavage surfaces detour around pebbles. Outcrop located on Yellowhead Road just west of bridge across Miette River.

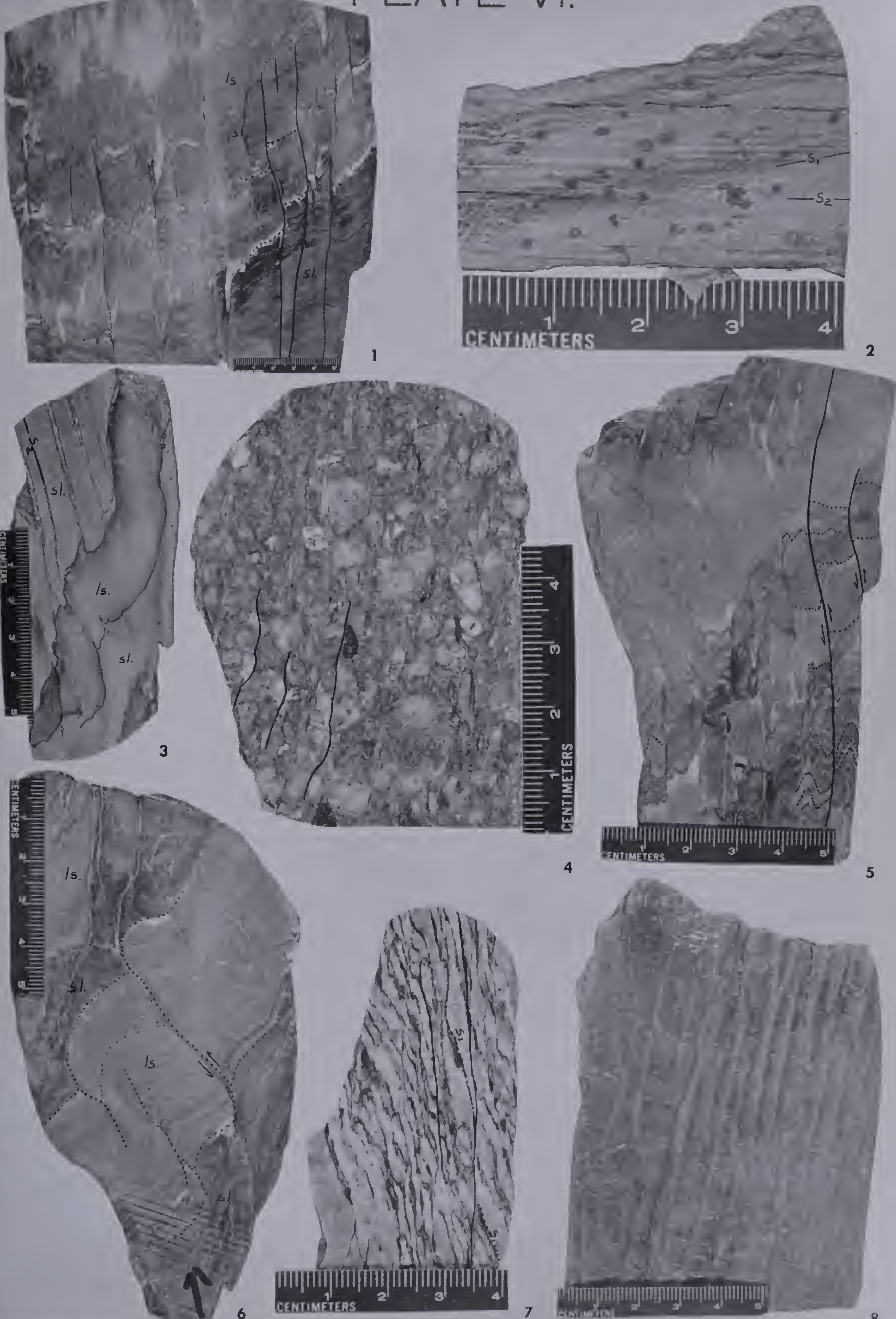
5 - Slip (strain-slip) cleavage in interbedded limestones (ls.) and slates (sl.) of Member B_3, Old Fort Point Formation, Meadow Creek Anticlinorium. Sample is from southwest dipping normal limb in overturned anticline; hinge of anticline is to right of picture. Note the uniform displacements along cleavage and the prominent folding and crumpling of the slate in the slices between cleavage planes. Same location as Figure 1.

6 - Cleavage mullions in interbedded limestones (ls.) and slates (sl.) of Member B_3 of the Old Fort Point Formation, southwest limb of Muhigan Creek Anticlinorium. View is approximately normal to the axial surface of the fold. Hinge of the anticline is to the right of the picture. Outcrop located on Yellowhead Road about 600 feet east of bridge across Muhigan Creek.

7 - Strongly cleaved argillaceous limestone from Member B_3 of the Old Fort Point Formation, Meadow Creek Anticlinorium. Sample is from outcrop of very tight overturned mesoscopic fold cropping out along Canadian National Railways tracks about 6300 feet west of Geikie Station.

8 - Very closely spaced kink folding in a well-cleaved slate from the Wynd Formation, Meadow Creek Anticlinorium. The surface of the sample is parallel to S_2. The prominent lineation is L_{2x3}.

PLATE VI.



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EXPLANATION OF PLATE VII

Photomicrographs of Thin Sections Showing Sedimentary Rocks

Figure

1 - Argillaceous limestone-breccia from the northeastern facies of Member B, Old Fort Point Formation, Jasper Anticlinorium. Phenoclasts (light colored) are of very finely crystalline limestone in a matrix of silty calcareous argillite. Sample location is at east end of bridge across Athabasca River at Old Fort Point. Crossed nicols x10.

2 - Arenaceous limestone-breccia from Member C_2, Old Fort Point Formation, Jasper Anticlinorium. Phenoclasts are of silty, very finely crystalline limestone (upper right) in a matrix of coarse sand grains and calcite. Note overgrowths on some of the sand grains. Crossed nicols x10.

3 - Fine-grained calcareous sandstone from Member B_1, Old Fort Point Formation, Mina Lake section. Note the absense of fracture cleavage. Crossed nicols x25.

4 - Silty, very finely crystalline limestone from Member B_3 of the Old Fort Point Formation, Meadow Creek Anticlinorium. Crossed nicols x25.

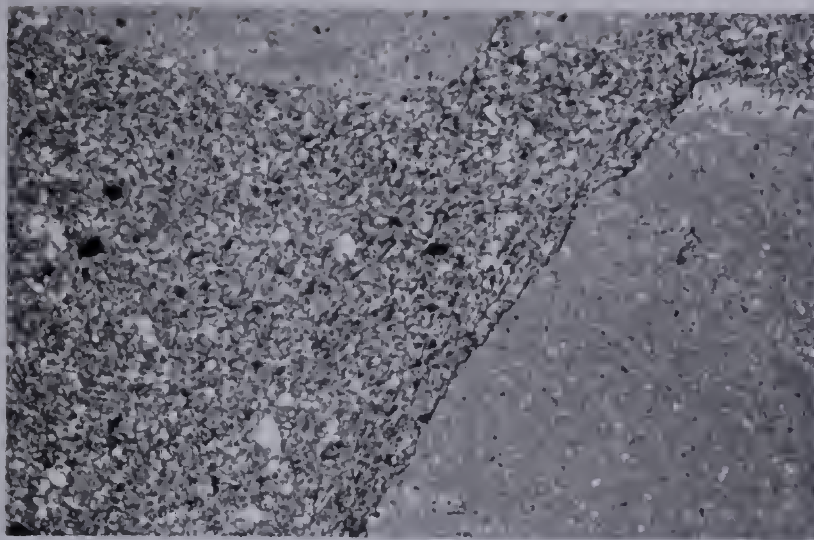
5 - Overgrowth of quartz on well-rounded quartz grain in a calcareous sandstone from Member C_1, Old Fort Point Formation; Tekarra Creek section. Crossed nicols x25.

6 - Deformed quartzite pebble in the quartz pebble limestone-breccia of Member D of the Old Fort Point Formation; Portal Creek section. Crossed nicols x10.

7 - Pebbles of metamorphic rocks in pebble-conglomerate from the Meadow Creek Formation, Meadow Creek Anticlinorium. Crossed nicols x10.

8 - Poorly sorted sandstone from the Meadow Creek Formation, Meadow Creek Anticlinorium. The sand-sized grains and pebbles are quartz and albite. The matrix is fine-grained calcite and argillaceous material. Crossed nicols x12.5.

PLATE VII.



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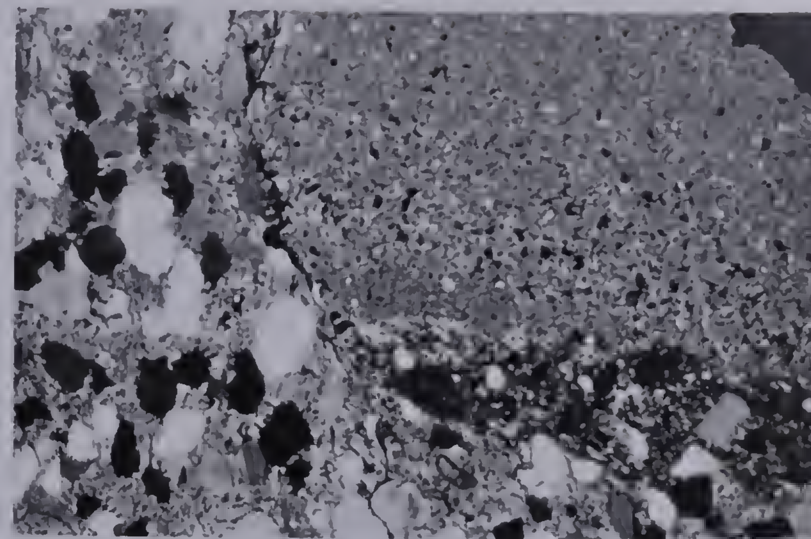

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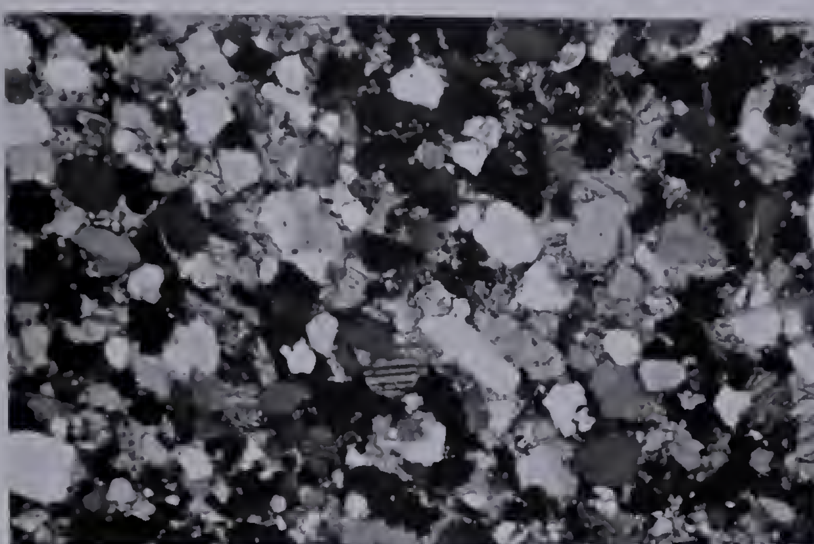

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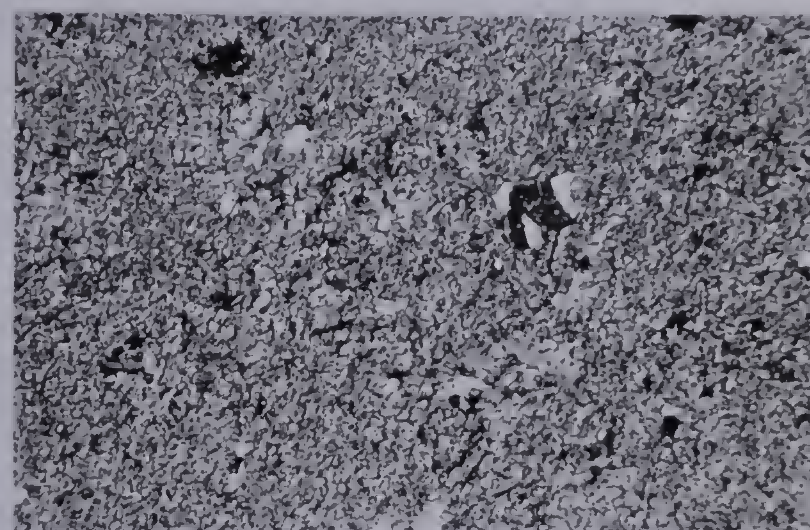

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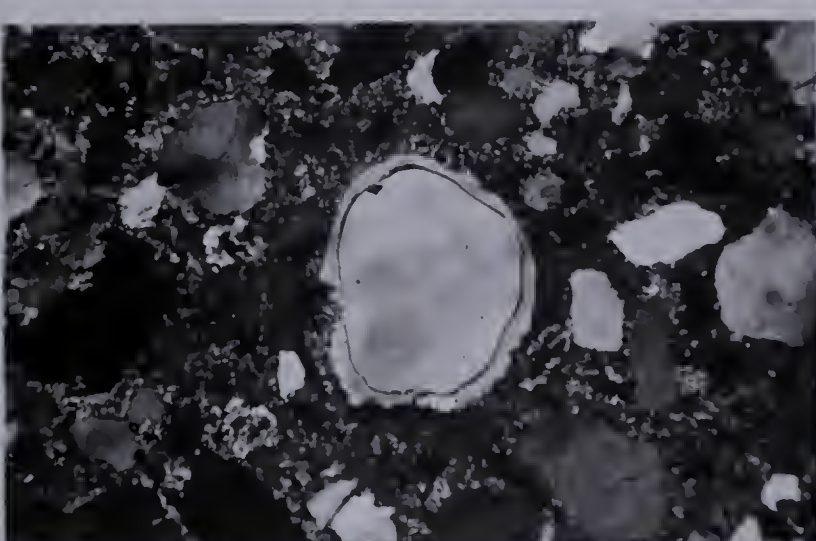

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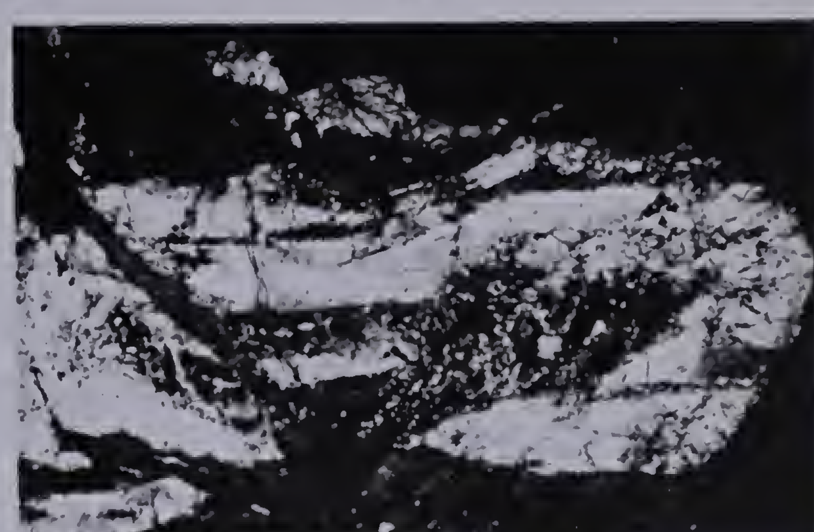

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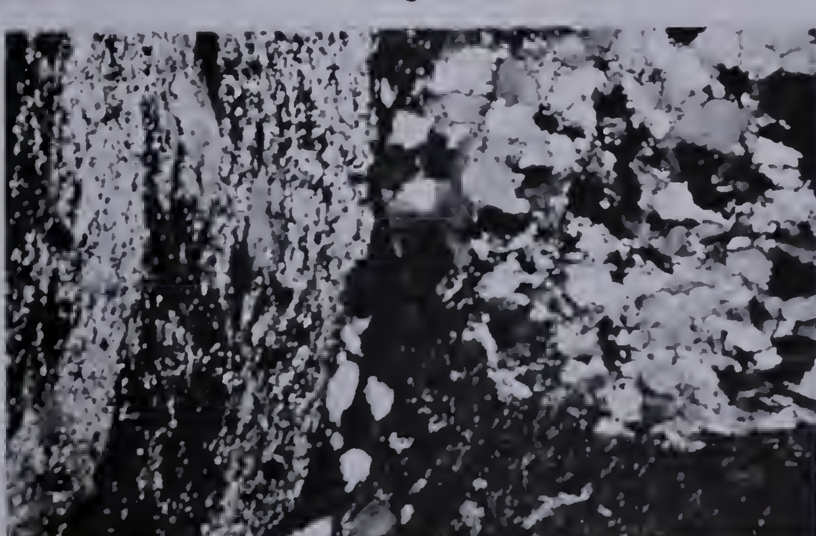

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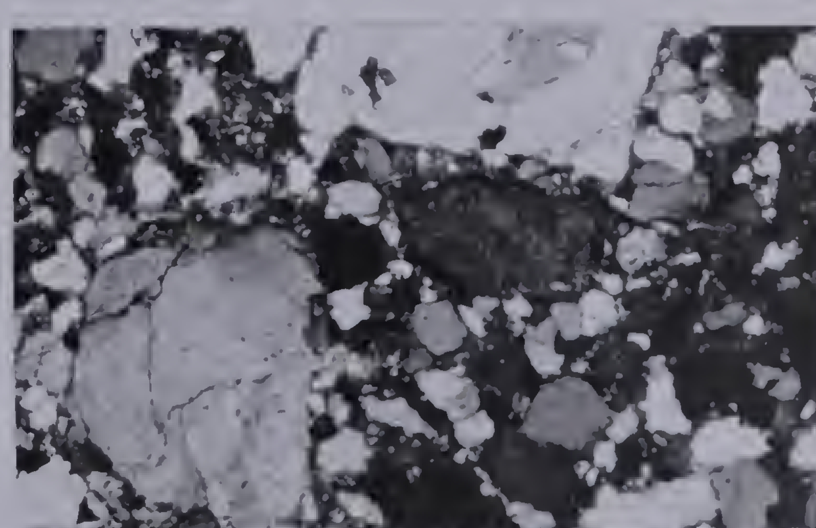

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EXPLANATION OF PLATE VIII

Photomicrographs of Thin Sections Showing Cleavage

Figure

1 - Slaty cleavage (S_2) in a slate from Member B_1, Old Fort Point Formation, Meadow Creek Anticlinorium. Note how the micaceous minerals (light flakes) tend to be concentrated into zones parallel to cleavage and which bound domains consisting largely of silt-sized particles (dark grains) of quartz and albite. Crossed nicols x62.5.

2 - Transposition of bedding (S_1) by slaty cleavage (S_2) in slates from Member D of the Old Fort Point Formation, Meadow Creek Anticlinorium. The light colored laminae are finely crystalline calcite. Crossed nicols x10.

3 - Chlorite-muscovite books parallel to bedding in an uncleaved argillaceous siltstone from Member A, Old Fort Point Formation, Jasper Anticlinorium. The "c" axes are approximately at right angles to the long dimension of the books. The arrow points to what appears to be a kink band in a mica book. Plane light x40.

4 - Slip (strain-slip) cleavage (S_2) in slates of Member C, Old Fort Point Formation, Meadow Creek Anticlinorium. Note the large chlorite-muscovite book. Plane light x25.

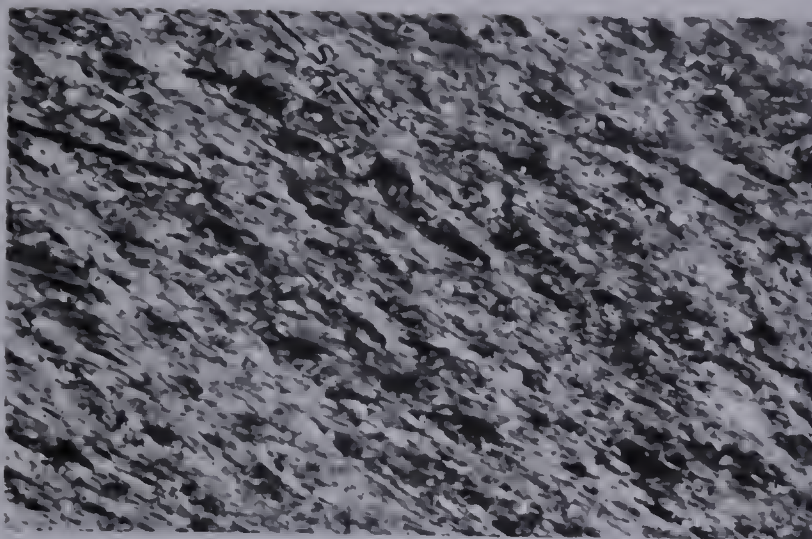
5 - Fracture-cleaved pebbly sandstone from the Wynd Formation, northeast limb of the Meadow Creek Anticlinorium. The micaceous minerals are oriented parallel to the fracture planes. Plane light x10.

6 - Diagonal dark zones are fracture cleavage zones in limestone of Member B_3, Old Fort Point Formation, Meadow Creek Anticlinorium. Muscovite and chlorite are concentrated in the zones. Crossed nicols x25.

7 - Quartz grain showing what may be Boehm lamellae in a fracture-cleaved pebbly sandstone from the northeast limb of the Meadow Creek Anticlinorium. Note how the micaceous minerals wrap around the quartz grain. Crossed nicols x25.

8 - Biotite-muscovite phyllite from Miette Group (?) strata near Mount Robson Station. This rock (AK 661) yielded a whole-rock K-Ar date of 69 m.y. Note the preferred orientation of well-crystallized muscovite flakes. Plane light x255.

PLATE VIII.



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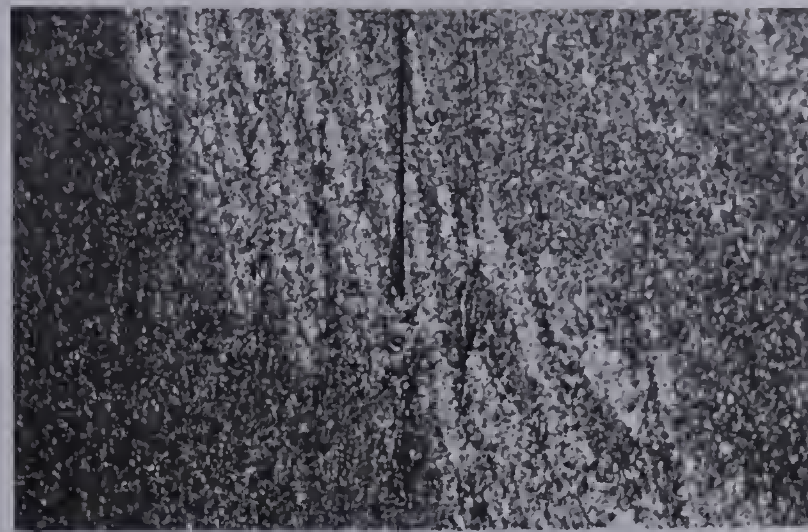

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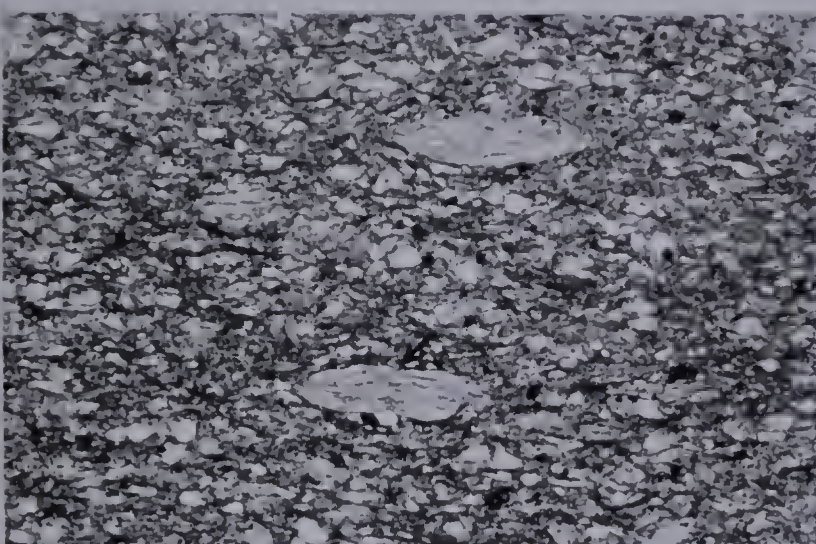

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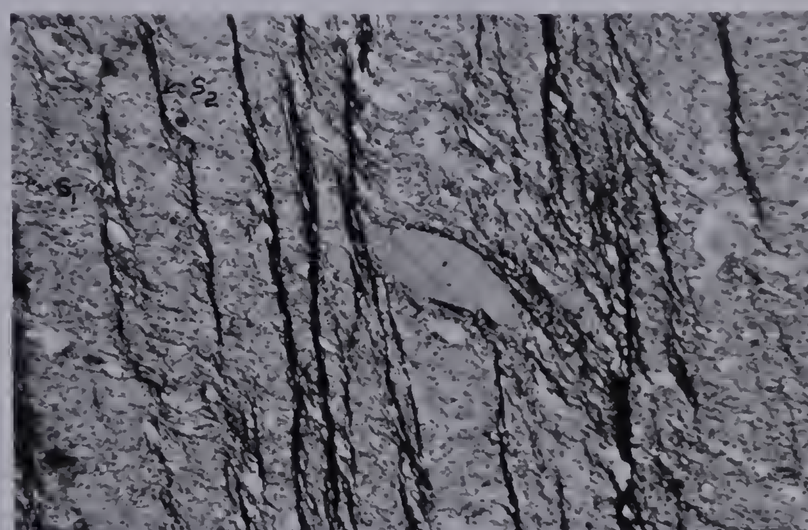

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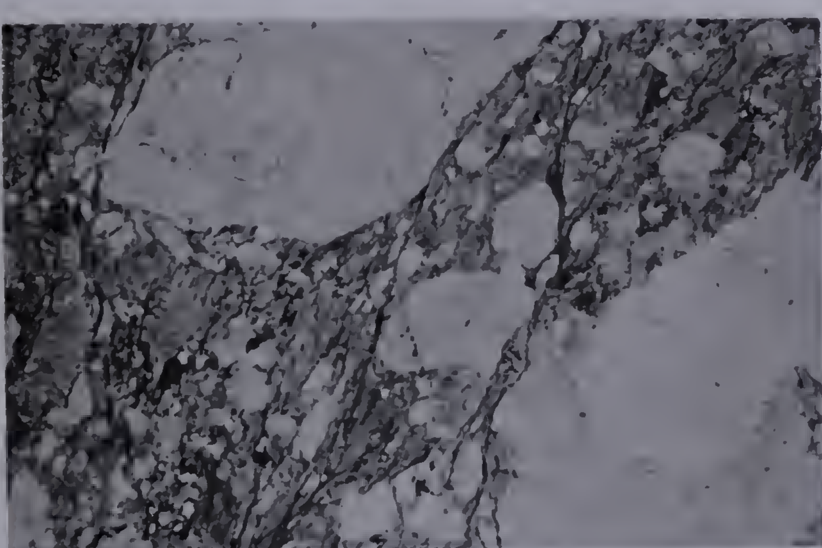

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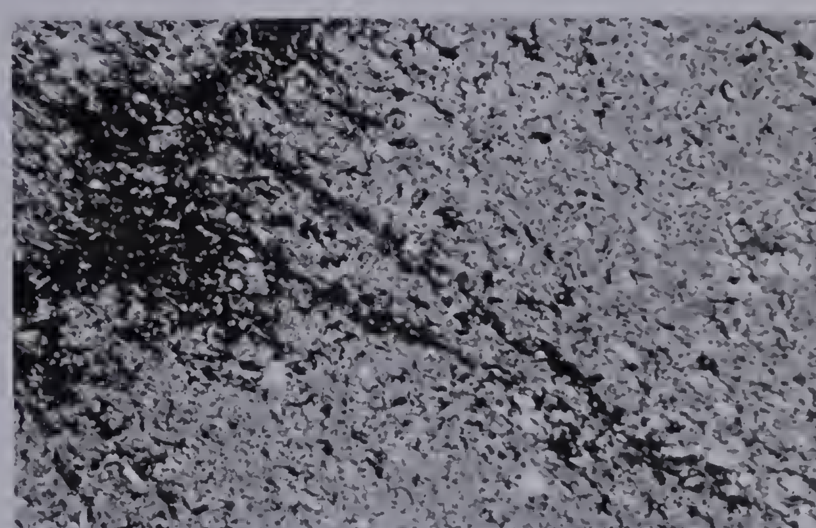

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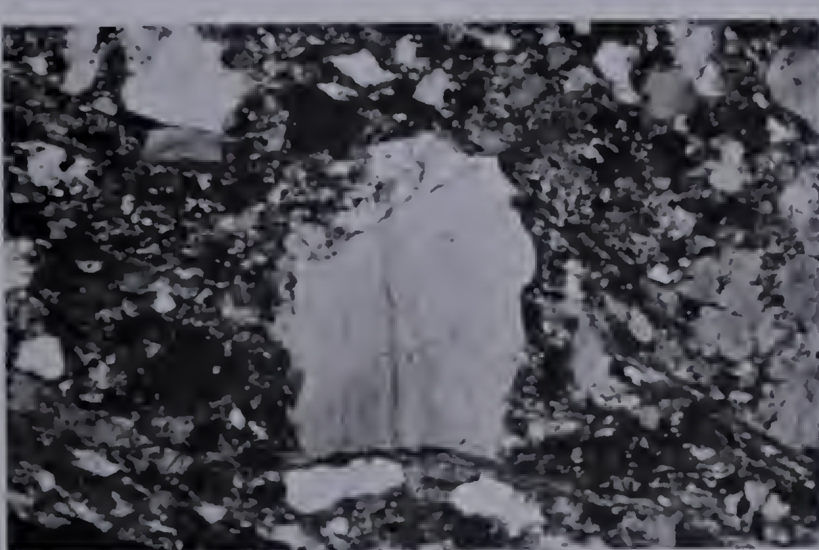

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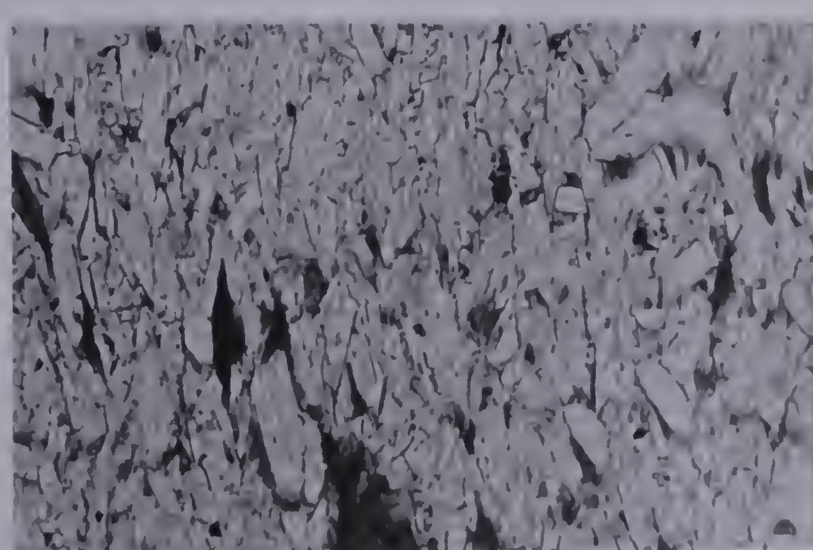


8

EXPLANATION OF PLATE IX

Photomicrographs of Thin Sections Showing Cleavage and Deformation of Limestones

Figure

1,2 - Slip (strain-slip) cleavage in slates of Member C_1, Old Fort Point Formation, Meadow Creek Anticlinorium. Note how the bedding (S_1) between the S_2 planes is folded into anticlines and synclines. Figure 1 taken under plane light, Figure 2 with cross nicols. Both x100.

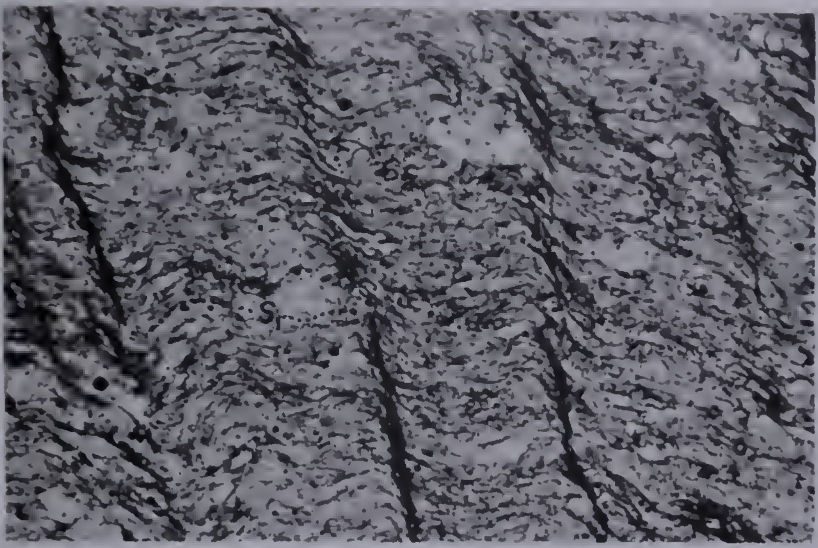
3,4 - Psammite from the Mount Robson area showing excellent preferred orientation of platy minerals. Biotite separate (grey flakes in Figure 4) AK-659 from this rock yielded 93 m.y. K-Ar date, muscovite separate AK-660 yielded 105 m.y. date. Figure 3 taken with crossed nicols, Figure 4 taken under plane light. Both x10.

5 - Finely crystalline limestone from Member B_3, Old Fort Point Formation, Meadow Creek Anticlinorium. Sample is from overturned limb of anticline where beds have been visibly attenuated. Note the lack of any visible preferred orientation in the calcite. Plane light x160.

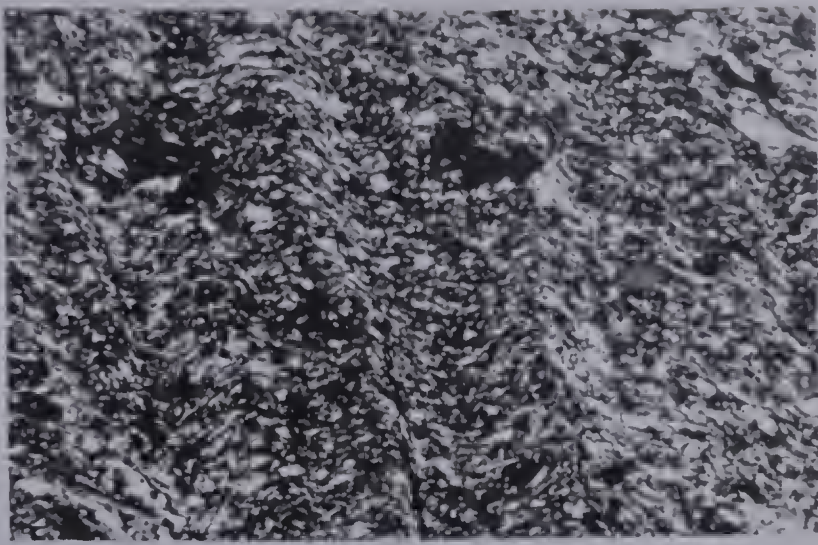
6 - Arenaceous limestone-breccia from Member C_2, Old Fort Point Formation, Meadow Creek Anticlinorium. Breccia is on overturned limb of anticline and has been visibly affected by folding (see hand specimen in Plate II-7). Crossed nicols x10.

7,8 - Two oriented sections cut normal to each other from limestone phenoclast shown in Figure 6. Section in Figure 7 was cut normal to the bedding and parallel to the fold axis. It shows little evidence of any preferred orientation of calcite grains. Section in Figure 8 was cut normal to the bedding and normal to the fold axis. The upper and lower edges of the figure are approximately parallel to both S_1 and S_2. Note the marked shape orientation in the calcite grains, long dimension being oriented parallel to S_1 and S_2. Both taken in plane light x255.

PLATE IX.



1



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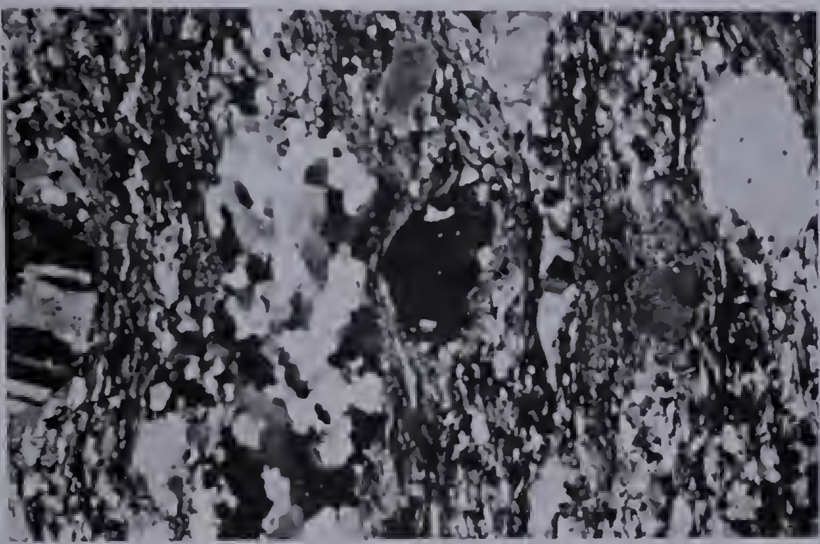

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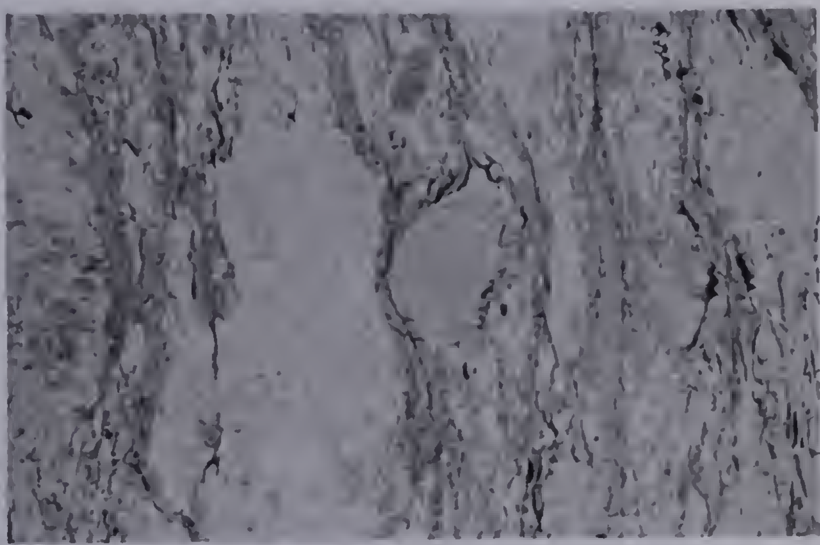

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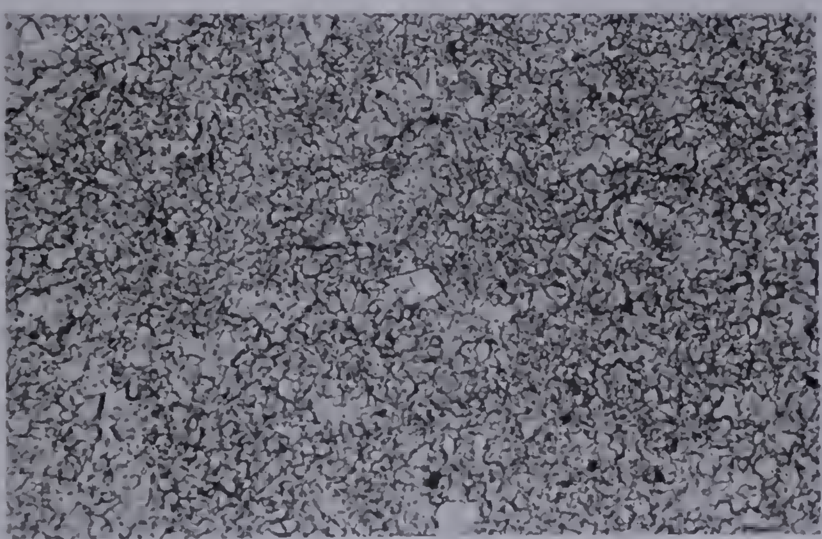
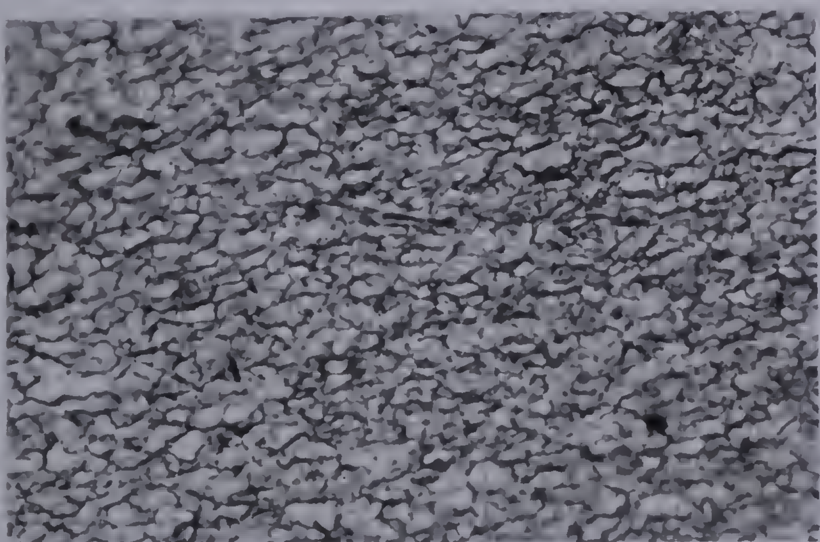


5

6



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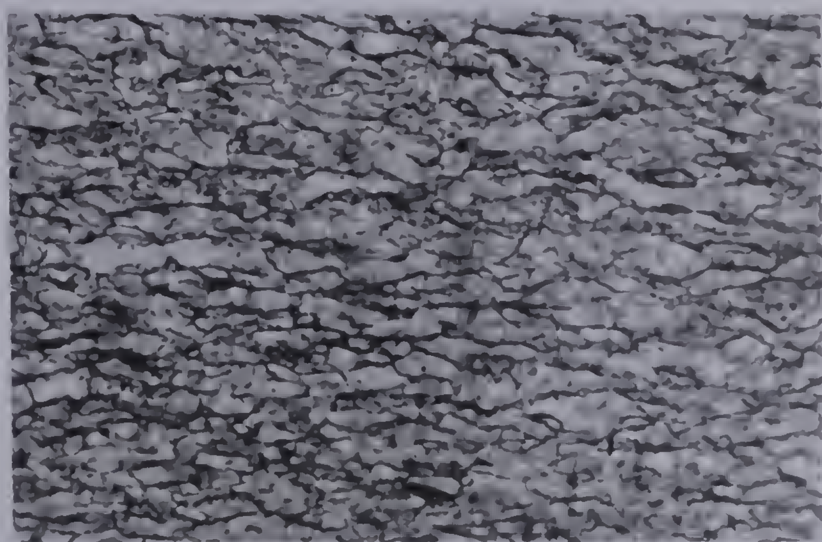


8

EXPLANATION OF PLATE X

Photomicrographs of Thin Sections Showing Kink Folding, Veining, Cataclasis and Igneous Intrusive

Figure

1 - Small-scale kink fold in calcareous slate of Member B_2, Old Fort Point Formation, Meadow Creek Anticlinorium. The S_3 surfaces are zones of bending of S_2. Plane light x40.

2 - Calcite in joint vein fillings, Meadow Creek Anticlinorium. Arrow points to what may be kink zone in calcite crystal. Plane light x10.

3 - Calcite and highly strained quartz in joint vein filling, Meadow Creek Anticlinorium. Crossed nicols x10.

4 - Siderite (upper right) and quartz in a vein filling from a normal fault, Meadow Creek Anticlinorium. Quartz shows non-undulatory extinction. Crossed nicols x10.

5 - Wynd Formation arenite from reverse fault zone, exhibiting minor cataclasis, Meadow Creek Anticlinorium. Crossed nicols x10.

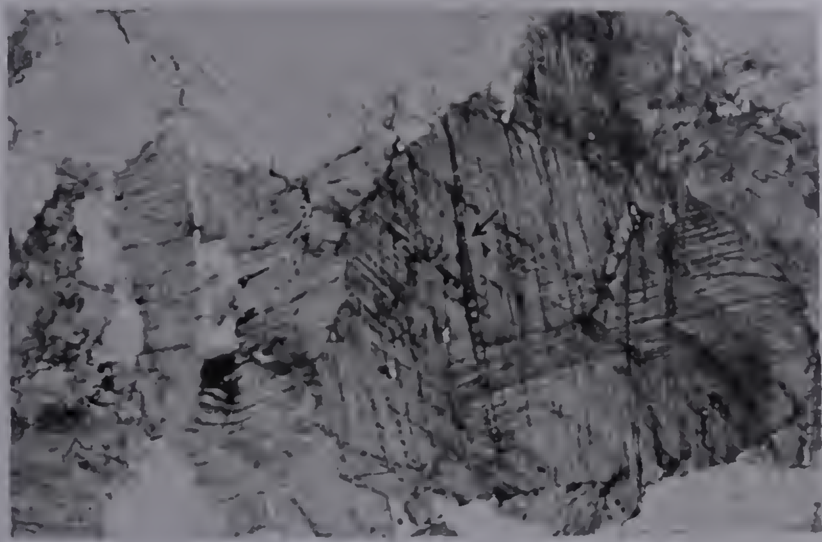
6 - Siderite in Member B_2 slate from the Old Fort Point Formation, Yellowhead Lake Anticlinorium. Note how the slaty cleavage wraps around the earlier formed siderite grains. Plane light x25.

7 - Igneous intrusive from Meadow Creek Anticlinorium. Sample consists of calcite, siderite, albite feldspar laths, and a large quantity of the opaque mineral leucoxene. Crossed nicols x12.5.

8 - Albite feldspar laths associated with calcite and opaque leucoxene in the igneous intrusive from the Meadow Creek Anticlinorium. Crossed nicols x40.

PLATE X.

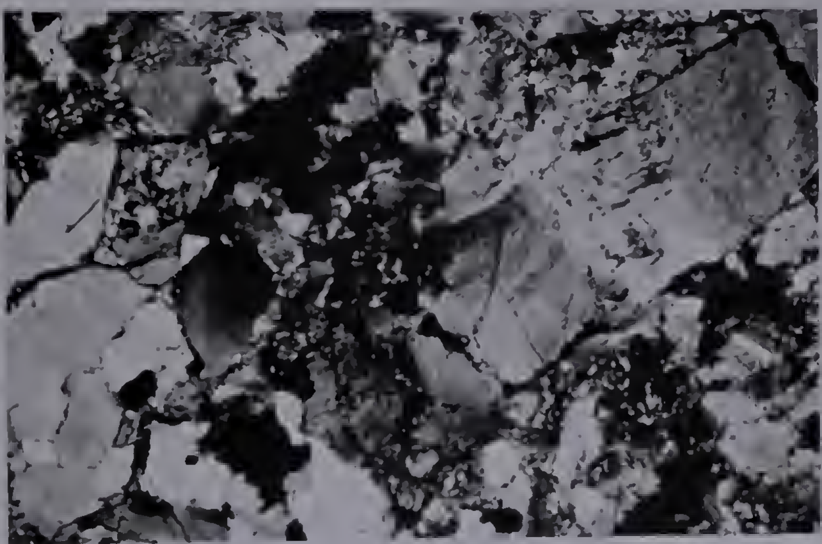
1



2

3

4



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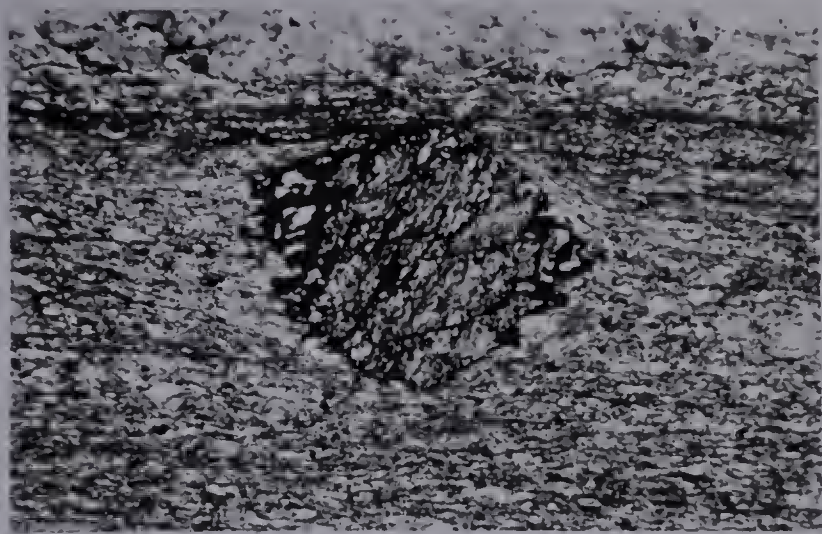
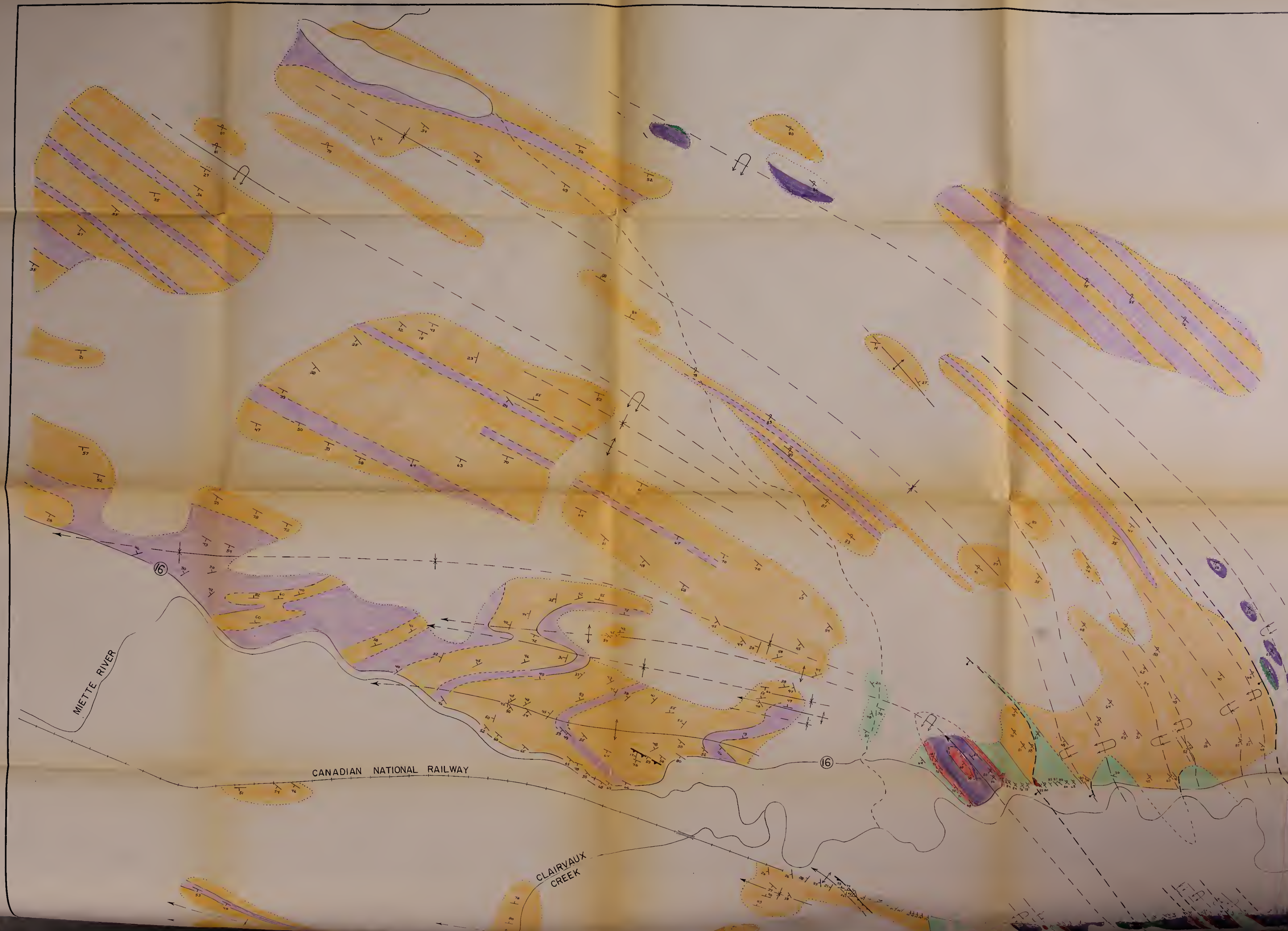
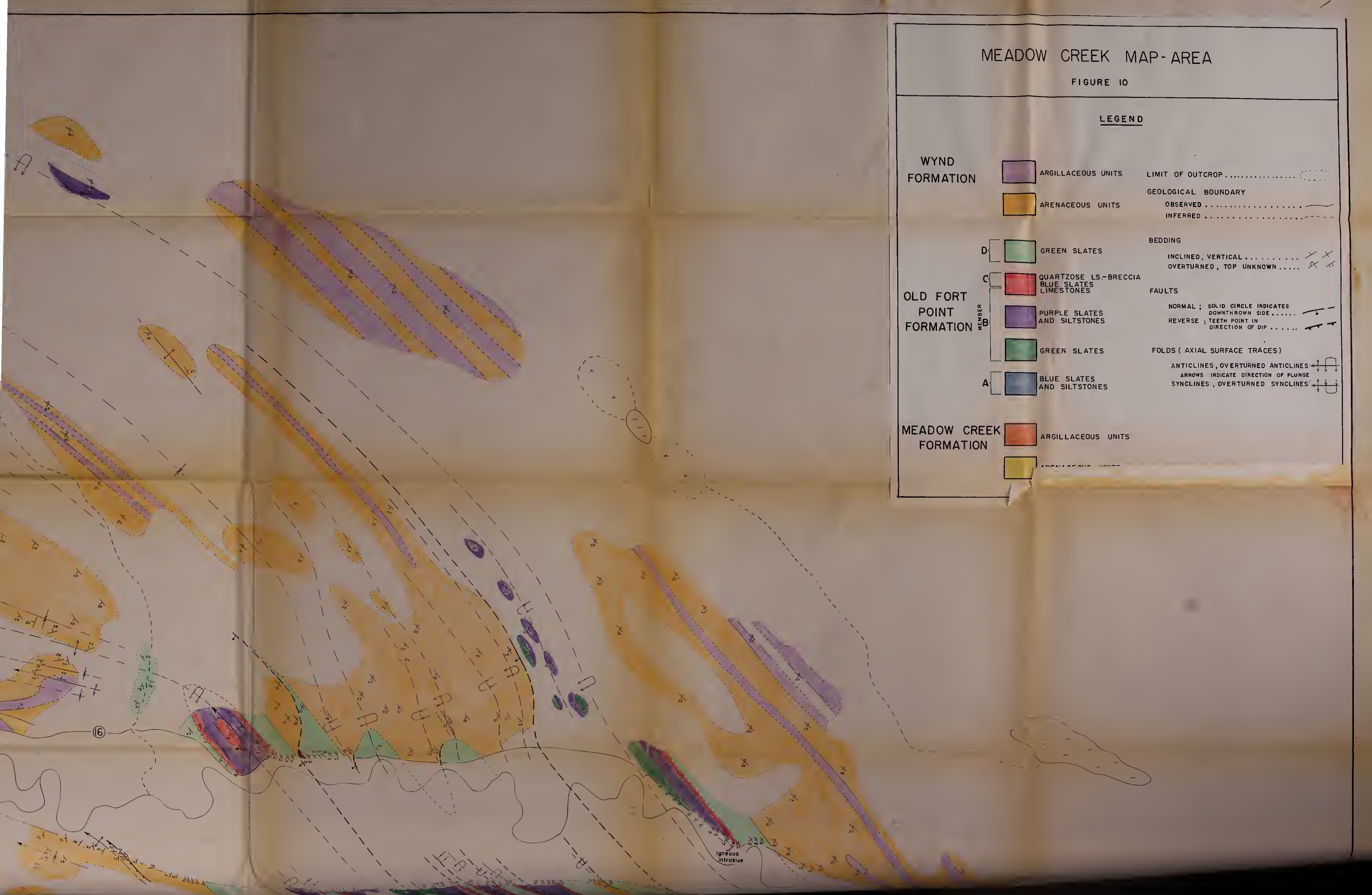


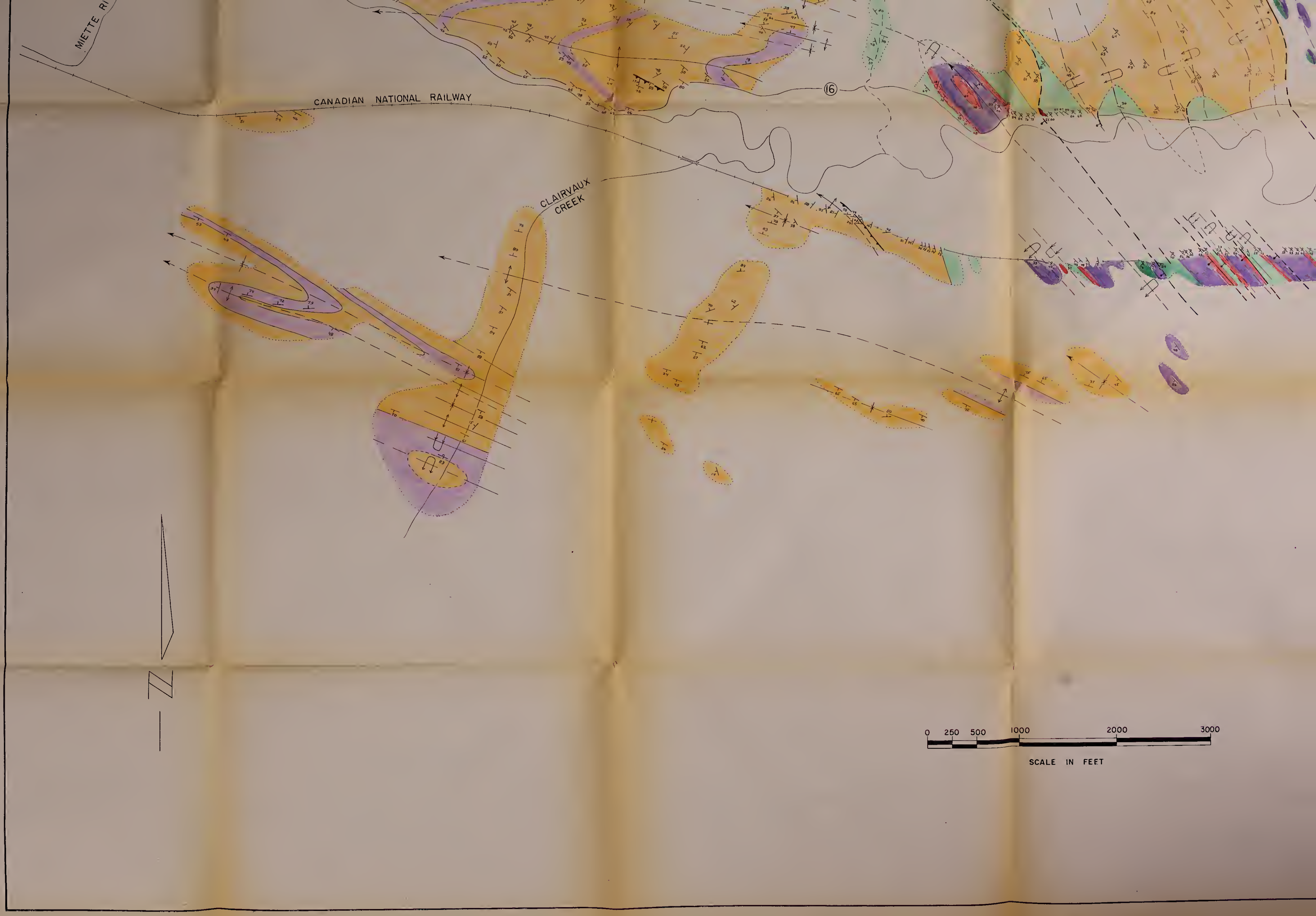
6

7

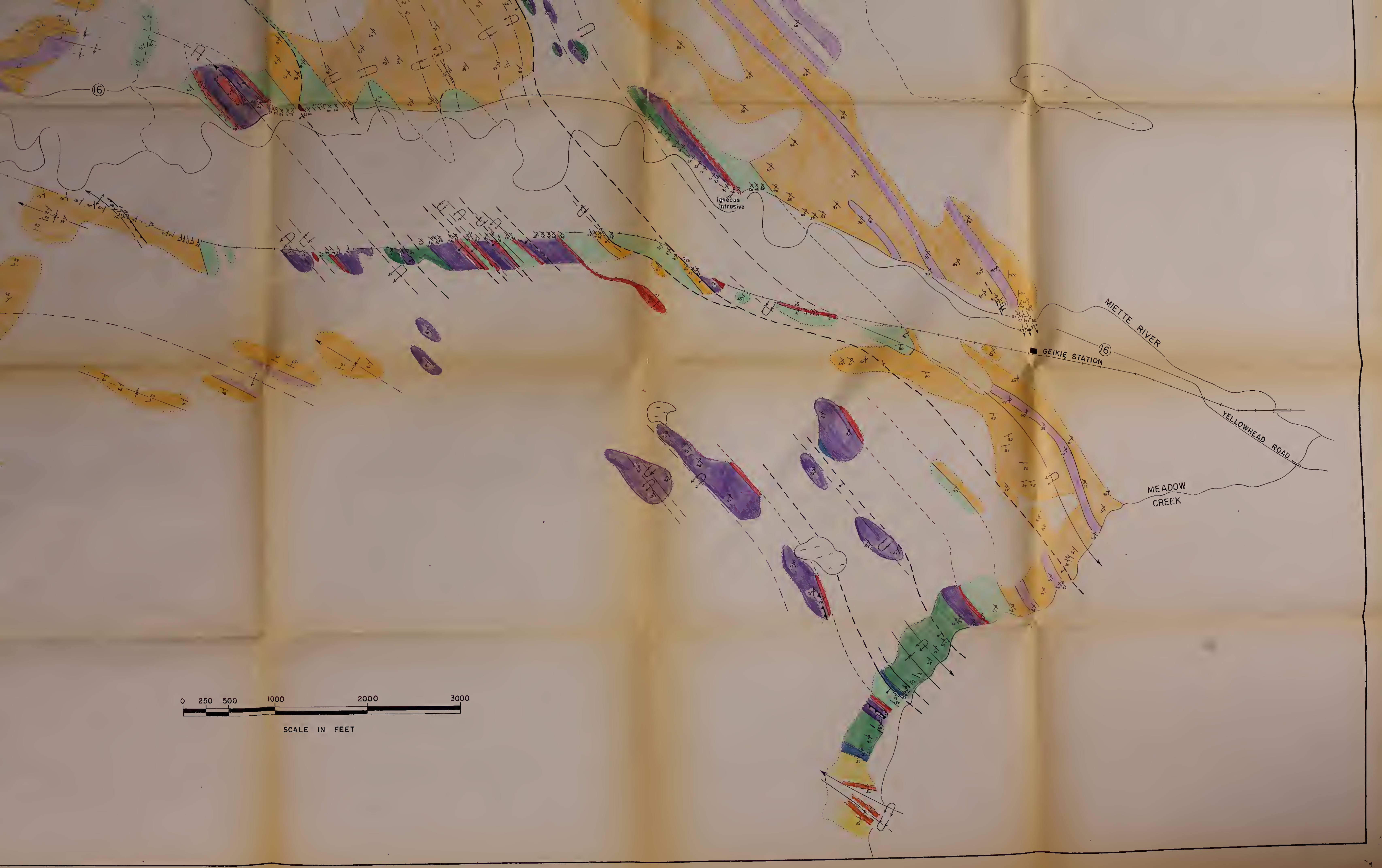
8


MIETTE RIVER
CANADIAN NATIONAL RAILWAY
CLAIRVAUX CREEK
16

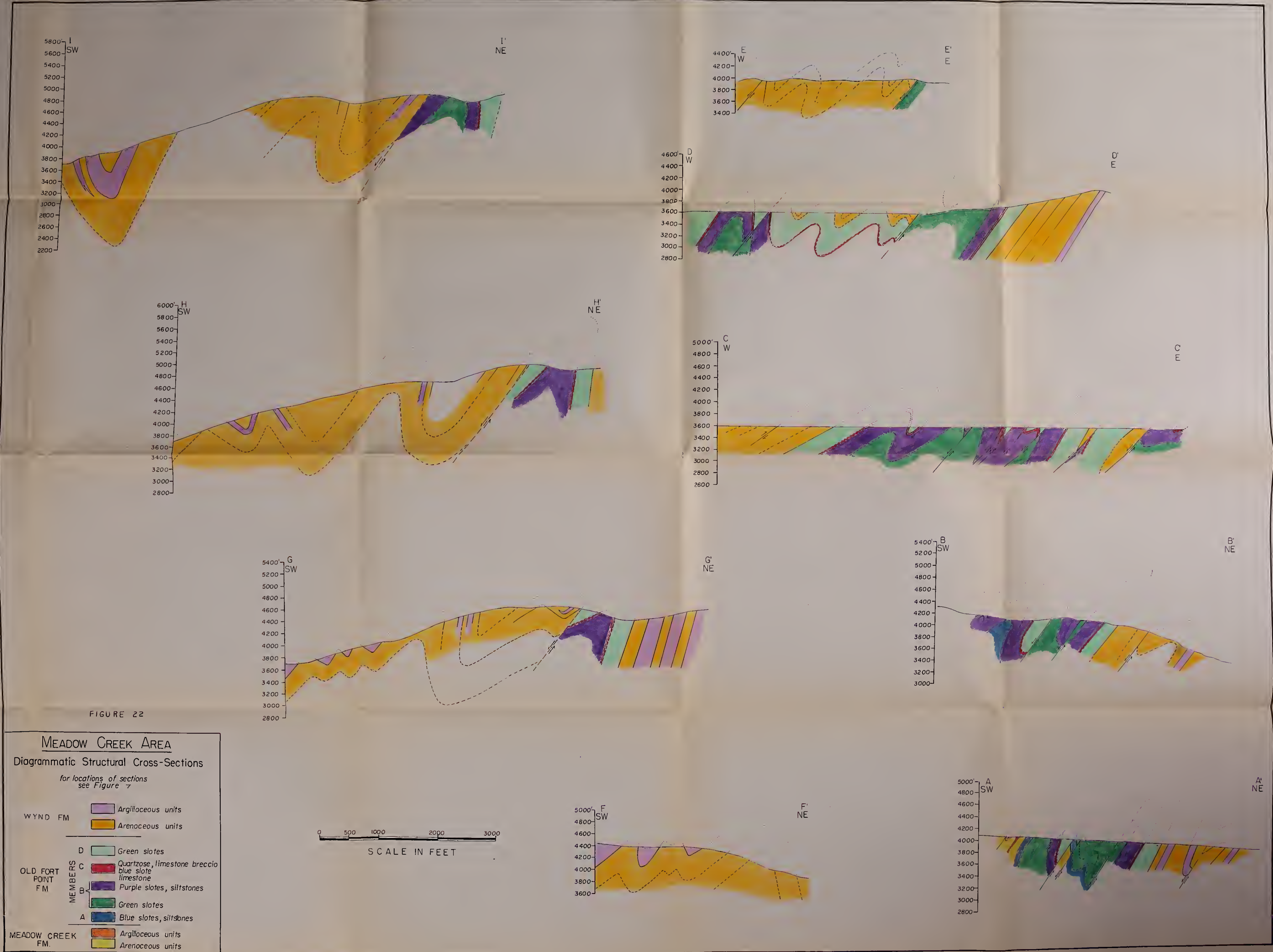

MEADOW CREEK MAP-AREA
FIGURE 10
LEGEND
WYND FORMATION
ARGILLACEOUS UNITS
ARENACEOUS UNITS
OLD FORT POINT FORMATION
MEMBER
D
GREEN SLATES
C
QUARTZOSE LS.-BRECCIA
BLUE SLATES
LIMESTONES
B
PURPLE SLATES AND SILTSTONES
GREEN SLATES
A
BLUE SLATES AND SILTSTONES
MEADOW CREEK FORMATION
ARGILLACEOUS UNITS
LIMIT OF OUTCROP
GEOLOGICAL BOUNDARY
OBSERVED
INFERRED
BEDDING
INCLINED, VERTICAL
OVERTURNED, TOP UNKNOWN
FAULTS
NORMAL ; SOLID CIRCLE INDICATES DOWNTHROWN SIDE
REVERSE ; TEETH POINT IN DIRECTION OF DIP
FOLDS (AXIAL SURFACE TRACES)
ANTICLINES, OVERTURNED ANTICLINES
ARROWS INDICATE DIRECTION OF PLUNGE
SYNCLINES, OVERTURNED SYNCLINES
igneous intrusive



MIETTE R
CANADIAN NATIONAL RAILWAY
CLAIRVAUX CREEK
16
N
0 250 500 1000 2000 3000
SCALE IN FEET



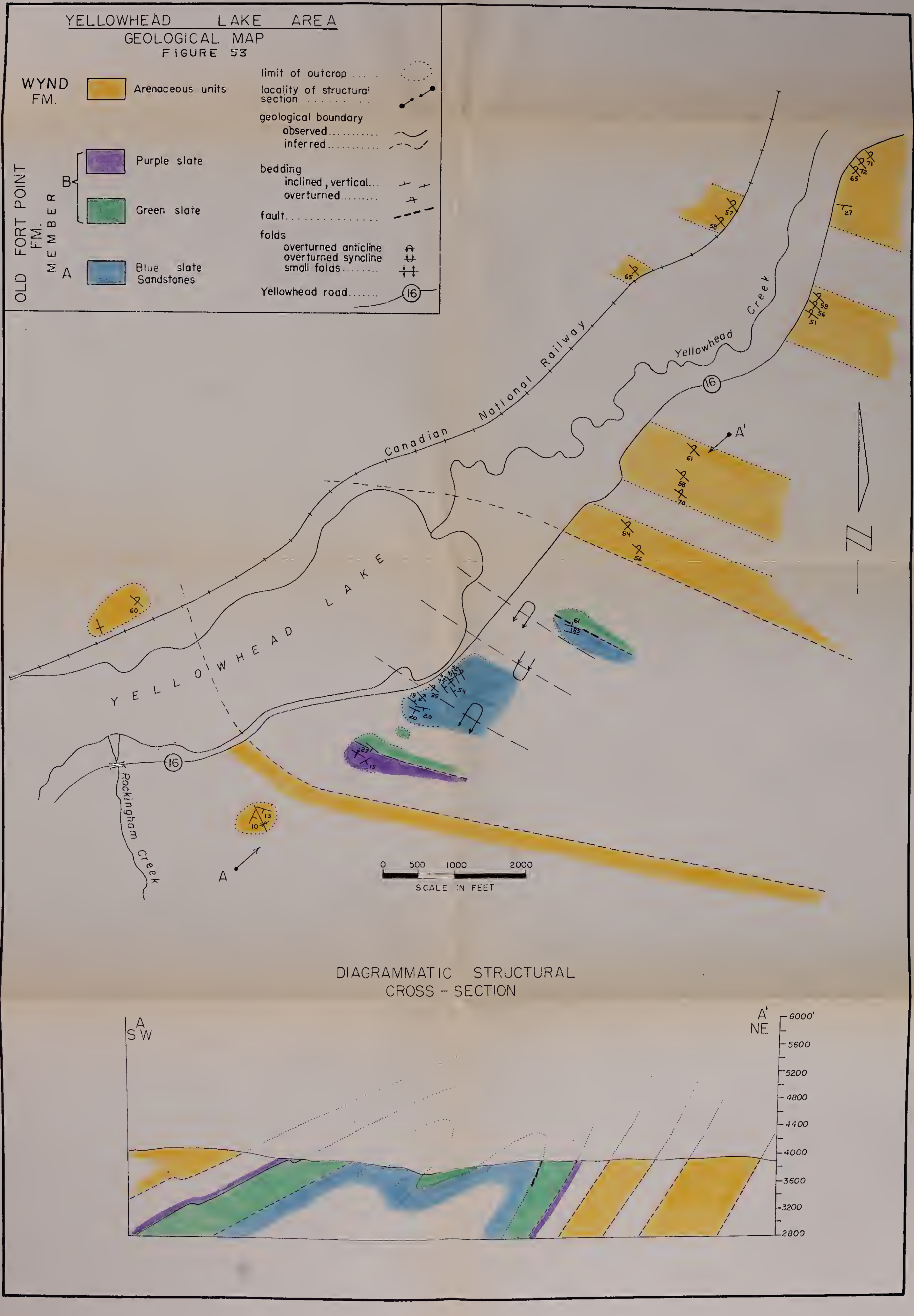
Igneous intrusive
MIETTE RIVER
GEIKIE STATION
16
YELLOWHEAD ROAD
MEADOW CREEK
0 250 500 1000 2000 3000
SCALE IN FEET



I SW
I' NE
H SW
H' NE
G SW
G' NE
F SW
F' NE
E W
E' E
D W
D' E
C W
C' E
B SW
B' NE
A SW
A' NE
0 500 1000 2000 3000
SCALE IN FEET
MEADOW CREEK AREA
Diagrammatic Structural Cross-Sections
for locations of sections see Figure 7
WYND FM
Argillaceous units
Arenoceous units
OLD FORT POINT FM
MEMBERS
D Green slates
C Quartzose, limestone breccia blue slate limestone
B Purple slates, siltstones
Green slates
A Blue slates, siltstones
MEADOW CREEK FM.
Argillaceous units
Arenaceous units

FIGURE 22


MUHIGAN CREEK AREA
GEOLOGICAL MAP
FIGURE 50
WYND FM.
Argillaceous units
Arenaceous units
OLD FORT POINT FM.
MEMBER
D
Green slates sandstones
C
B
Quartzose Ls-breccia limestones
Limit of outcrop
Locality of structure section
Geological boundary
observed
inferred
Bedding
inclined, vertical
overturned
Folds
anticline
syncline
Yellowhead road
16
N
MIETTE RIVER
Muhigan Creek
A
A'
250
500
1000
SCALE IN FEET
DIAGRAMMATIC STRUCTURAL CROSS - SECTION
A SW
A' NE
4600'
4400
4200
4000
3800
3600
3400
3200
3000


YELLOWHEAD LAKE AREA
GEOLOGICAL MAP
FIGURE 53
WYND FM.
Arenaceous units
OLD FORT POINT FM. MEMBER
B
Purple slate
Green slate
A
Blue slate
Sandstones
limit of outcrop
locality of structural section
geological boundary
observed
inferred
bedding
inclined, vertical
overturned
fault
folds
overturned anticline
overturned syncline
small folds
Yellowhead road
16
Canadian National Railway
Yellowhead Creek
YELLOWHEAD LAKE
Rockingham Creek
N
A
A'
0
500
1000
2000
SCALE IN FEET
DIAGRAMMATIC STRUCTURAL
CROSS - SECTION
A
SW
A'
NE
6000'
5600
5200
4800
4400
4000
3600
3200
2800